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OPTIMIZATION OF POSTMORTEM BEEF CHILLING CONDITIONS THROUGH CONTROL OF CARCASS TEMPERATURE HISTORY

by

Douglas S. McGinnis

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

FOOD ENGINEERING

DEPARTMENT OF AGRICULTURAL, FOOD AND NUTRITIONAL SCIENCE

Edmonton, Alberta

Fall 1995

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The undersigned certify that they have read, and recommend to the faculty of Graduate Studies and Research for acceptance, a thesis entitled **Optimization of postmortem beef chilling conditions through control of carcass temperature history** submitted by **Douglas S. McGinnis** in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Food Engineering.

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ABSTRACT

Optimization of postmortem beef chilling conditions through control of carcass temperature history

A research air-chilling system was developed and used to control the history of the average temperature of beef sides during postmortem chilling. This system permitted continuous operation by means of specialized design features, including automated defrost control and dual, alternating air chillers. Three experimental chilling programs reduced the average beef side temperature to 0°C in 20 h, each by different temperature-time paths. The effects on meat quality, hygiene and moisture losses (purge and shrink) of these regimes, applied in combination with electrical stimulation, were investigated in experiments involving 36 steers.

Individual carcasses were temperature-monitored in six muscle locations during chilling. These and other processing data were used as feedback to a computer control system which maintained the calculated average carcass temperature to within 0.11°C (max. 20 h mean) of the target profile. Control precision was limited only by the resolution of the temperature sensors.

Beef was hermetically stored for five days after chilling, then assessed for loin (rib-eye) meat quality. A significant ($p<0.05$) increase in protein solubility resulted from the application of an initially more rapid rate of carcass temperature decline. Also, experimentally chilled beef produced meat that was significantly ($p<0.05$) darker (lower L*) and redder (higher a*) than conventionally chilled beef. Most quality attributes did not vary, and

meat quality was not adversely affected by the experimental chilling treatments.

Published bacterial growth rate models were programmed and used with processing data to estimate potential bacterial proliferation on the carcass surface. The proliferation of various species of spoilage and safety concern was predicted to be dramatically reduced by early reduction of the carcass surface temperature. Also, the temperature function integration method predicted that each of the experimental treatments would arrest the growth of *Pseudomonas* spp., whereas conventional chilling would permit continued bacterial growth after 22 hours.

Finally, processing data were used to develop and validate a mathematical model for prediction of evaporation rate from suspended beef sides. The evaporation rate varied with the rate of cooling, but overall shrink (or average evaporation rate) did not vary among treatments.

Of the studied chilling regimes, it was concluded that the optimum most rapidly reduces carcass temperature during the early stages of chilling.

Dedication

This work is dedicated to my dear wife,

Colleen

and to my precious daughters,

Megan, Sorcha & Briar.

Acknowledgements

There are numerous persons to whom I am grateful for their support towards the successful completion of this project. Firstly, I wish to thank my supervisor, Dr. Roberto Segado. His thoughtful guidance, friendship, enthusiasm and unwavering support have been important factors that have greatly contributed to this endeavour.

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Abbreviations

Abbr.	Definition
ATP	Adenosine tri-phosphate
CIE	Commission Internationale de l'Eclairage (1976).
CON	Control treatment consisting of conventional beef chilling.
CV#	Inlet and outlet valve pair for cold chilling fluid in heat exchanger #1 or #2.
ES	Electrical stimulation of beef side.
HV#	Inlet and outlet valve pair for hot defrost fluid in heat exchanger #1 or #2.
IP	Iso-electric point
LD	*Longissimus dorsi* muscle
LT	*Longissimus thoracis* muscle.
MFI	Myofibrillar fragmentation index.
PID	Proportional+Integral+Derivative feedback control strategy.
PLC	Programmable logic controller.
PC	Phosphocreatine or personal computer.
PC1	Program for chilling treatment No. 1.
PC2	Program for chilling treatment No. 2.
PC3	Program for chilling treatment No. 3.
PSE	Pale, soft and exudative
PG	Aqueous propylene glycol.
RTD	Resistance temperature detector.
SD	Standard deviation.
SE	Standard error.
SR	Sarcoplasmic reticulum
SM	*Semimembranosus* muscle.
SV	*Serratus ventralis* muscle.
WHC	Water holding capacity of meat

Nomenclature

Symbol	Definition	Units
Aa	Live animal surface area	m^2
As	Exposed surface area of beef side	m^2
Ca	Specific heat of the air	kJ kg^{-1} K^{-1}
Cc	Average specific heat of carcass tissue	kJ kg^{-1} K^{-1}
Cp	Specific heat of aqueous PG fluid	kJ kg^{-1} K^{-1}
Dt	Thermal diffusivity of air	m^2 s^{-1}
Daw	Mass diffusivity of water vapour in air	m^2 s^{-1}
E	Rate of moisture loss by evaporation from beef side	kg s^{-1}
G	Number of bacterial generations	Generations
h_c	Average convective heat transfer coefficient	kJ K^{-1} m^{-2} s^{-1}
k	Thermal conductivity of air	kJ K^{-1} m^{-1} s^{-1}
kc'	Average convective mass transfer coefficient	m s^{-1}
Ls	Significant length or length of equivalent slab	m
m	Mass of carcass tissue	kg
M_c	Total carcass mass	kg
M_{cp}	Average carcass mass during the control period	kg
m_p	Average mass flowrate of aq. PG (present control period)	kg s^{-1}
pHu	Ultimate pH or pH at 6 days postmortem	--
pH_{45}	pH at 45 minutes postmortem	--
Q_T	Total instantaneous rate of heat gain from surroundings	kW
Tai	Air temperature at the cabinet inlet location	°C
Tao	Air temperature at the cabinet outlet location	°C
Tf	Final temperature	°C
Ti	Initial temperature or muscle temperature when $\theta = 0$	°C
Thc	Temperature of the beef hip at the centre	°C
Thm	Temperature of the beef hip midway between centre and surface	°C
Ths	Temperature of the beef hip at the surface	°C
Tlc	Temperature of the loin at the centre	°C
Tls	Temperature of the loin at the surface	°C
Tnc	Temperature of the neck at the centre	°C
Tma	Mass-average carcass temperature	°C
Tma^t	Target average carcass temperature during chilling process	°C
Tm	Mean temperature of infinitesimal carcass element	°C
T_{pi}	Propylene glycol temperature at heat exchanger inlet	°C
T_{po}	Propylene glycol temperature at heat exchanger outlet	°C
Ts	Temperature of the bacterial medium or meat surface	ºC
Vs	Volume of carcass side	m^3

Wl	Live animal mass	kg
Xs	Concentration of water vapour in air at the carcass surface	kg m^{-3}
Xa	Concentration of water vapour in air surrounding carcass	kg m^{-3}
α, β	Experimental parameters	-
ΔT_{ma}	Calculated change in the mass-average carcass temperature	°C
$\Delta\theta$	Time increment or control period	s
η_1	Experimental parameter	°C s
η_2	Experimental parameter	°C s^2
Γ	Growth rate of bacterial specie(s)	Generations h^{-1}
γ	experimental constant	h $°C^{-1}$
ρa	Density of the air	kg m^{-3}
ρc	Average density of carcass	kg m^{-3}
σ	Experimental parameter = 0.077503	$kg^{3/2}$ m^2
θ	Time	h
θc	Time from start of programmed chilling	h
θ_T	Chilling time to achieve muscle temperature Tf	h
λf	Latent heat of fusion of water	kJ kg^{-1}

Dimensionless terms

ft	Fraction of side outer surface area lost between slaughter and trimming.
fi	Fraction of newly exposed carcass surface area to area beneath epidermal layer.
Pr	Prandtl Number.
Re	Reynolds number.
Rt	Ratio of average side thickness to average side length.
Rw	Ratio of average side width to average side length.
Sc	Schmidt Number.

Chapter I

INTRODUCTION

Nowhere in the "cold chain" is the influence of refrigeration on meat quality more critical than when dressed carcasses are first chilled. Efforts by engineers and meat scientists to optimize chilling conditions for low-cost production of high quality meat are challenged by the complexity and non-uniformity of the heat and mass transfers involved in the process, by the biological complexity and non-uniformity of the carcass meat tissues, by variability in the contaminating microbial flora, by the necessity of using expensive trained taste panels for quality assessments, and by the complex division of economic interests linked to the costs and benefits of chilling. Nevertheless, carcass chilling may be viewed as an opportunity to exert limited control over the irreversible changes taking place in muscle during its conversion to meat. This stems from many years of research that has shown, perhaps not always in obvious ways, that postmortem biochemical and ultrastructural changes in muscle are strongly influenced by the timing, severity, mode, and duration of the chilling process. This introduction highlights some of the more important aspects of the influences of chilling on red meat carcasses and meat quality, and briefly puts these into the context of abattoir chiller design.

The fundamental purpose of chilling is to restrict the growth of any one of many possible enteric pathogens and spoilage microorganisms of mainly fecal, water, and soil origin found on the animal hide, the hands of plant workers, animal intestines, and other

sources (Nottingham, 1982). This flora can include yeasts, moulds, viruses, parasites, and bacteria, the latter being the leading cause of food-borne diseases and primarily responsible for meat spoilage. The doubling time for a wild strain of *Escherichia coli* on a beef carcass would be in the order of 27 min for a typical post-slaughter surface temperature of 35°C. Reducing the surface temperature to 7°C would increase the doubling time to about 28 h (6,250% increase), clearly illustrating the benefit of early postmortem chilling. This benefit was recently demonstrated by Gill and Jones (1992), who concluded that exposure of pig carcasses to a freezing air blast before chilling is likely to improve the hygienic efficiency of a carcass chilling process. On the other hand, the undisturbed interior of healthy muscle is microbiologically sterile, which considerably reduces concern about elevated interior muscle temperatures, at least while surface temperatures remain low (e.g., <4°C). It is noteworthy that guidelines and regulations concerning carcass chilling recommend or stipulate only that deep carcass temperatures be reduced below a specified value prior to shipping, whereas adequate rates of surface chilling, or chill initiation times for the hours immediately following slaughter, or both, are ignored. The important issue of timing in postmortem chilling is thus largely overlooked.

In terms of meat palatability, it is known that chilling influences carcass meat at the deeper tissue levels, both in negative and positive ways. For example, the EEC (1978) requirement of chilling meat, particularly beef and lamb, to 7°C or less before shipping can be a problem for producers because a reduction to this temperature in a 24 h

period often necessitates rapid chilling, with potential for "cold-toughening" of, at least, the superficial meat tissues. Rapid chilling may also cause surface fat to become hard and difficult to handle (Shaw *et al.*, 1986; Davey, 1989). Expensive drip losses can be reduced and the water holding capacity (WHC) of the meat can be increased through the proper design and management of the chilling system (Penny, 1977; Honikel *et al.*, 1981; Offer and Knight, 1988). The pale, soft exudative (PSE) condition that develops naturally in 5-20% of pork carcasses can be artificially induced in most cases (Bendall and Wismer-Pedersen, 1962; Bodwell *et al.* 1966) and in a limited number of cases with beef (Locker and Daines, 1976) by maintaining the carcass at 37 °C until completion of rigor; that is, by delaying chilling for as long as 0.5 h in some cases. Indeed, rapid cooling of pig carcasses can decrease the incidence of PSE muscle (Honikel, 1986; Gigiel *et al.* 1989; Petrovic *et al.*, 1992). On the other hand, very rapid chilling of meat to temperatures below 10 - 15 °C (depending on muscle and species) prior to rigor completion can lead to increased meat toughness due to thaw shortening (Forrest *et al.*, 1975).

The ultimate postrigor ultrastructural character of meat, particularly as reflected in its texture, is clearly influenced by chilling through its direct effects on the breakdown rates of the muscle energy compounds. Moreover, the myofibrillar proteins comprise about 70% of the bulk of the muscle mass, and most of the important intramuscular biochemical and structural changes that take place during the first 12-24 h appear to occur within the sarcoplasm and within the matrix of these contractile proteins. However, any suggestion that this system is easily defined would be a dangerous assertion. For

example, we know that significant variation exists from muscle to muscle, and indeed from fibre to fibre, in composition of myoglobin, oxidative and glycolytic enzymes, and levels of energy substrates. Each muscle is a unique mixture of red and white fibres, having a unique distribution of fibre lengths.

To complicate matters further, large temperature gradients exist throughout the carcass during chilling for an extended period before temperature equilibrium is achieved after 12 - 24 h. Not surprisingly, most of the research on the effects of temperature on postmortem muscle behaviour has been accomplished using strips of excised muscle removed shortly after slaughter. Yet, this has been done in spite of the fact that cutting of the muscle generates a contractile response, irreversibly altering the initial condition of the sample.

Therefore, optimum chilling solutions are not readily apparent. The specification of appropriate chilling regimes are driven by a number of competing interests while the combined physical and biochemical mechanisms by which chilling affects important changes in meat quality, variously expressed at the times of grading, retail display, and consumption, are highly complex. Nevertheless, our ability to understand the effects of chilling on meat quality is important. This endeavour encourages us to examine the important relationships between the temperature history of the muscle and the ultrastructural postmortem rigor processes during chilling.

Chilling during the pre-rigor period

Bendall (1951) demonstrated that the rigor mortis process and the characteristics of post-rigor muscle are strongly influenced by the muscle temperature during rigor mortis. In Bendall's 1951 study of excised *psoas* muscle from rabbits exposed to varying levels of drug-induced antemortem muscle activity, the delay period, rate of shortening, and severity of the shortening reaction were found to be strongly temperature dependent. While Bendall at that time was only able to speculate upon the mechanism by which irreversible rigor contraction occurs, he and others have shown that it is explained by the disappearance of adenosine tri-phosphate (ATP), or more accurately, by the inability of the muscle to re-synthesize ATP faster than its rate of disappearance (Bate-Smith and Bendall, 1949; Bendall, 1966, 1978; Cassens and Newbold, 1966, 1967). From this work, it was hypothesized that temperature exerts its influence, at least in the range of 17 to 37°C, by modifying the reaction rates of glycogenolysis, glycolysis, and the breakdown of phosphocreatine (PC) and ATP. It is now strongly believed that the action of myosin ATPase is responsible for the major portion of ATP hydrolysis postmortem (Greaser *et al.*, 1969; Bendall 1973a,b), and it has been hypothesized that a steady, slow diffusion of calcium from the *sarcoplasmic reticulum* (SR) is responsible for catalyzing this dephosphorylation within the actin-myosin ATPase filament structure (Greaser, 1986). Furthermore, it has been postulated that ATP splitting by a host of other ATPases associated with the SR, mitochondria, and plasmalemma, together with other uncharacterized transport ATPases, contributes significantly to the overall rate of ATP depletion. Also, ATP levels have been found to remain quite constant as long as PC

remains above 4 mmol per gram of muscle (Bendall, 1973b). As observed directly and indirectly in numerous studies (Bendall, 1966, 1978; Jolley *et al.* 1980), PC and ATP depletion rates between 37 and 15°C decrease with decreasing temperature. This explains why the delay period is extended at the lower end of the temperature range, and why shortening occurs at a slower rate. That shortening is more severe when ATP depletion occurs quickly may be due to the relative inability of the actin-myosin bonds to become free before further contraction occurs, as remaining ATP is split by myosin ATPase. That is, in slow contraction, increased time may favour the optimal use of remaining reserves of ATP in preventing contraction. The severity of the irreversible contraction is also reflected in post-rigor sarcomere length.

To a greater extent than rigor shortening, the phenomenon of cold shortening, the potentially severe shortening of muscle fibres from exposure to temperatures below about 10°C before completion of rigor, is associated with toughening of cooked meats (Locker, 1960; Locker and Hagyard, 1963), particularly lamb and beef. Furthermore, the influence of cold shortening on toughening is seemingly quite complex, as demonstrated by Marsh and Leet (1966), who found that a 40% shortening of fibre length can produce meat of maximum toughness, while meat exhibiting extremes in levels of shortening (e.g., 20% vs. 55-60%) can have low mechanical toughness. Davey and Gilbert (1974) have elucidated the mechanism by which strong, irreversible contracture of the muscle is induced by a reduction of the muscle temperature below about 10°C (beef) before ATP reserves have been substantially depleted by about 50% below the initial postmortem

level and muscle pH has fallen below a value of about 6 . This appears to be the direct result of an inhibitory effect on the Ca^{++} sequestering performance of the triads of the SR, this being due in some unexplained way to the reduction in temperature. The release of Ca^{++} ions into the muscle fibre cytoplasm, where it appears to stimulate the dephosphorylation of the ATP by myosin ATPase, enables the binding of the actin-myosin contractile filaments (Pearson, 1987). It follows that the reversibility of this process is effectively destroyed as long as the SR is unable to sequester Ca^{++}, although there is evidence that cold shortening is reversible if the muscle temperature is re-elevated above 10°C.

Locker and Daines (1976) studied the effect of temperature during rigor onset on tenderness in excised beef muscle that had already undergone irreversible cold shortening. They found that completion of the final stages of rigor at an elevated temperature (37°C) results in tenderness (shear force) that is comparable to that of beef that has not undergone cold shortening. Ruling out temperature acceleration of aging or reversal of the cold shortening as possible explanations, Locker and Daines (1976) speculated that temperature may have a direct effect on the bonds formed between the myosin heads and the actin-tropomyosin-tropinin complex. That is to say, the significance of cold shortening towards tenderness may depend not only upon sarcomere shortening, but upon the number and strength of these bonds. It would, nevertheless, be impractical to re-elevate the temperature of cold shortened meat during the last stages of rigor as a commercial processing measure.

Thus cold contracture may be viewed as an induced acceleration of the normal rigor process in which irreversible fixing of the links between actin and myosin occur due to a depletion of ATP in the fibre cytoplasm. The primary difference between cold contracture and loss of extensibility in rigor appears to be the mechanism and rate by which ATP is depleted. That cold contracture results in a more severe toughening of the meat than is produced by the rigor process may be partly explained by the speed at which cold contracture occurs relative to normal rigor development. A short-time course of rigor mortis results in a greater amount of contraction than a long-time course (Pearson, 1987; Marsh, 1954). Interestingly, early and rapid chilling of muscle to temperatures above about 10 °C should, therefore, result in a reduced extent of rigor shortening, whereas rapid chilling to temperatures below this value, when ATP levels remain sufficiently high, has the opposite effect. This may help to explain why blast chilling of pork, with internal temperatures remaining above 10 °C for an extended period, can produce meat that is comparable in palatability to that of conventionally chilled pork (e.g., Jeremiah *et al.* 1992).

Research has not fully elucidated the mechanisms by which the internal carcass temperature history during the rigor process influences the longer term development of aging characteristics, as manifested in changes to meat tenderness and other quality attributes (e.g., elasticity, compressibility, cohesiveness, chewiness, stringiness, smoothness, density, etc.). While tenderness is generally regarded as one of the most important quality attributes of meat, the biochemical processes and mechanisms involved

in tenderization are not well understood. These processes are highly complex, involving numerous physicochemical processes and synergistically operative systems of enzymes.

Ouali (1990) has reviewed the meat tenderization process, and has described the complex mechanisms involving proteolysis, osmosis, ionization, and other processes responsible for the tenderization of meat through aging. While the role of temperature in these mechanisms has been largely overlooked, Ouali pointed to research on physicochemical mechanisms by which tenderness causing fragilization of the myofibrillar structure takes place, and in which temperature during chilling likely plays an important role. Firstly, ionic strength achieved during rigor, with values ranging between 0.2 and 0.3, has been shown to be sufficient to dissociate contractile proteins (in a manner similar to "salting out"), resulting in diminished myofibril integrity. Ouali points out other *in vitro* studies suggesting that the intracellular ionic strength of postmortem muscle enhances the action of endogenous proteinases in the fragilization and, presumably, subsequent fragmentation of myofilament proteins, particularly those at the N_2 - line level at the junction of the I-filaments and the Z disk. Early temperature reduction will obviously delay the development of these ionic conditions, thereby extending the necessary period of aging. Given that rigor contraction will be reduced (assuming no cold shortening) by early chilling, there would be a reduced likelihood that the eventually-fragilized I-filaments will fracture by way of tension in the muscle fibre, created by rigor contracture. However, the question is open as to which contributes more to a reduction in tenderness during the resolution phase, the more severe rigor shortening

associated with higher temperature during early postmortem treatment, or the lower postmortem ionic strength associated with lower temperature during early chilling.

While aging occurs from an early postmortem time, as evidenced by the occurrence of proteolytic fragments within a few hours postmortem in bovine *longissimus dorsi* (LD) muscle (Troy and Tarrant, 1987; Troy *et al.* 1987) the significance of early proteolysis in relation to meat tenderness is unknown (Ouali, 1990). A similar conclusion might also be drawn concerning the tenderness effects of early changes in the ionic strength of the sarcoplasm.

A second physicochemical tenderization mechanism described by Ouali (1990) involves osmotic pressure and its importance in the water-holding capacity of meat. A shift in the ionic concentration on either side of the cell membrane will modify the distribution of water between intracellular and extracellular space, and this may affect drip production, and tenderness that is highly dependent on water content. Early postmortem temperature will influence ionic concentration and distribution, but the direct long term effects of these changes remain to be studied.

Chilling and water holding capacity

The ability of meat to immobilize or bind water, which represents approximately 75% of the mass of freshly excised muscle, is critical to its organoleptic quality. The content and the distribution of water in meat are important factors influencing its firmness, toughness, softness, juiciness, and appearance (Kauffman and Marsh, 1987; Offer and Knight, 1988). The inevitable loss of WHC leads to drip loss, the slow

formation of red coloured exudate from excised meat. Drip appears mainly after rigor mortis and cutting, and contains myoglobin and largely uncharacterized sarcoplasmic proteins. The protein concentration of drip varies between 80 - 160 mg mL^{-1} (Penny, 1975, 1977). In the drip process, unbound fluid is transported to the cut ends of the meat along extracellular passages next to the endomysium and connective tissues surrounding the muscle bundles.

In the abattoir, water loss is thought to occur mainly by evaporation in the chiller. The diffusion of water from extracellular tissue spaces likely contributes to this process. In a well-controlled chill facility, evaporative losses are usually maintained at a level of 1-2% of the dressed carcass mass, which can represent a substantial economic loss. Water losses through drip can be much more substantial. The amount of drip is highly variable, ranging between 0.1 and 10% of the lean meat mass (Offer and Knight, 1988), and depends greatly on a number of factors, including storage time, distance between cuts, cut orientation, and number of cuts. As previously discussed, muscle temperature strongly influences postmortem rates of glycolysis, glycogenolysis, ATP turnover, and enzyme activity, thereby influencing the rates and extent of rigor shortening, cold contracture, and pH fall. It appears that WHC is affected by all of these changes.

Significantly, the usual pH decline of muscle tissue to near isoelectric point (IP) values is believed to interfere with the water binding ability of the polar groups in the muscle proteins. Furthermore, the myofilaments are thought to be responsible for the bulk of the total bound water, with myosin of the thick filament contributing

proportionately more than the other proteins to intracellular water binding. The denaturation of myosin and other sarcoplasmic proteins arising from the postmortem fall in pH is probably influenced by the time course of temperature change during chilling. Chilling rate may, therefore, directly account for some of the variation in WHC. As previously stated, PSE meat can be avoided or reduced by means of early, rapid chilling. However, Penny (1977) observed that a crude measurement of activation energy for drip formation in pork muscle was considerably lower than the activation energies for denaturation of myosin, myofibril ATPase, and creatine kinase, suggesting that factors other than denaturation influence the amount of drip, or loss of WHC. Honikel (1986) concluded that pig muscles with ultimate pH=5.5 produce a lower drip loss when chilling is accomplished in such a way that sarcomere shortening is minimized. As pointed out by Offer and Knight (1988), it is clear that a decrease in postmortem temperature from 37 to 10 $^{\circ}$C (experimental isothermal treatments) substantially reduces the subsequent amount of drip, but it is not clear whether this is due to decreased protein denaturation or avoidance of the greater rigor shortening that occurs as temperature is increased.

Muscle shortening, whether by cold induction or by rigor shortening, may be responsible for a diminution of WHC by its effect on sarcoplasm volume. This volume reduction appears to be proportional to the reduction in sarcomere length, since there is no apparent change in sarcomere diameter upon rigor contraction. Thus, water that is bound in the myofibril lattice is forced into the extracellular space, which increases in volume. This process may be complicated by the development of irregular or heterogenous shortening patterns, in which a portion of the sarcomeres shorten, and by

the development of cleavages between sarcomeres arising from mechanical rupture or enzymatic breakdown (Bendall and Wismer-Pederson, 1962). Such irregularity in sarcomere contraction is manifested as wavy patterns within the gross myofilament structure of the fibre, and as zones of supercontracture. These developments, and the average reduction in sarcomere shortening, are also strong determinants of meat tenderness (Herring *et al.*, 1965).

Chilling technology

The designer of an abattoir chilling system is thus faced with an unlimited number of options, including batch and continuous handling strategies, a wide range of chiller environmental conditions (i.e., chilling fluid, temperature, humidity, fluid flowrate, etc.) and their time profiles, not to mention other processing treatments having an impact on carcass chilling (e.g., electrical stimulation, modified hot processing, applied muscle restraint). Design initiatives to improve economic efficiency, such as reducing pre-shipment shrink, reducing carcass warehousing costs, increasing the consistency of chilling time, or improving the thermodynamic energy efficiency of the system, must be examined with due regard for the economic consequences associated with producing meat of altered consumer acceptability. Thus, the establishment of linkages between the direct effects of particular chilling strategies on meat quality and the economic impacts that arise from those effects, as dictated by consumer needs and desires, remains a significant challenge to managers, engineers and meat scientists alike.

Efforts to meet such challenges have been subject to the limitations of conventional chilling technology. Typical refrigeration controls in research abattoirs mirror the indirect and crude industry approach of controlling the chilling environment (e.g. air temperature and humidity feedback control), with little or no input of the thermal effects upon carcasses during the chilling process. Because of physical differences between carcasses, lack of uniformity in the chilling conditions, changing thermal loads during the production period, and other control-related deficiencies, large differences of up to several hours in chilling time between sides can occur (Harris, 1975; Gill *et al.*, 1991b), under ostensibly identical chilling conditions. Furthermore, beef chilling processes are usually interrupted by defrost events that occur over long periods (e.g., up to about one hour) during which control of the chiller environment is virtually relinquished.

In addition to the above limitations, researchers have also tended to impose their own. Firstly, researchers investigating the effects of different chilling regimes on meat quality have generally neglected physical differences between carcasses and carcass treatments (e.g., mass, size, fat cover, orientation, and composition). That is, while the individual chilling responses of beef sides have been measured, and to a limited extent modeled (Arce *et al.*, 1983; Burfoot and Bailey, 1989; Levy, 1972; Mallikarjunan and Mittal, 1994a), the ability to accurately duplicate these experimental carcass *responses* under controlled conditions has not been reported. There is, therefore, a paucity of information concerning the influence of precise muscle temperature histories within the intact beef carcass on postmortem muscle changes. Secondly, researchers have tended to

focus on chilling regimes involving constant environmental conditions. This is somewhat understandable, since it would be very difficult in modern batch chillers to approach any degree of chilling uniformity amongst carcasses if the chilling conditions were other than constant, since chilling is a transient process and carcasses must be loaded into the chiller sequentially. However, much of the historical chilling research effort has been unduly constrained and otherwise influenced by problems that can be directly linked to the fact that "batch chilling" is incongruous with the continuous production mode of the modern abattoir.

Chilling under time-varying environmental conditions could be advantageous in attaining the optimum combination of meat quality attributes and hygienic, energy, and production efficiencies. Variable environmental conditions might be chosen, for example, to maintain the carcass surface temperature at a constant, low temperature, or to maintain conditions that would maximize the refrigeration-cycle energy efficiency at each stage of chilling (e.g., maintaining constant refrigeration load). These, and innumerable chilling strategies remain to be studied.

A strategy involving rapid initial chilling followed by a declining rate of carcass cooling (early rapid chilling) is a possible approach that promises certain advantages, in spite of concerns about cold shortening and long-term effects of early cold treatment causing toughening in aged meat. On one hand, earlier lowering of the muscle temperature would prolong the rigor process, thereby extending the period of vulnerability to cold-shortening effects (i.e., maintaining pH>6), and this might also

diminish longer-term tenderization processes (Dransfield, 1994). However, we know that lower initial carcass surface temperatures would reduce the potential for early bacterial proliferation. It would also reduce the subsequent refrigeration requirement during the latter stages of chilling, allowing the use of more moderate environmental temperatures when the bulk carcass temperature falls to a threshold level of about 10°C. If applied, electrical stimulation (ES) would tend to obviate concern about cold shortening (Aalhus *et al.*, 1991). Also, accelerated rapid chilling might further reduce overall shrink, as compared to the reduction observed with conventional rapid chilling (Bowater, 1986; Bowling *et al.*, 1987; Watt and Herring, 1974). This may be deduced from the fact that most of the evaporative loss occurs in the earliest stages of chilling while the carcass is still warm (ASHRAE, 1986), and a reduction of this period might be responsible for the reported association between lower shrink and rapid chilling. A further possible benefit of accelerated chilling might be the extension of the period of maximum proteolytic enzyme activity. While it is likely that lower temperatures will reduce the activity level of proteolytic enzymes, maintaining the carcass at or near an optimal pH level during the pre-rigor period could possibly enhance or help sustain their long-term effects or performance or both. In this regard, obviously, the application of ES would have to be carefully considered.

Whether achieved by conventional or new means, "rapid chilling" in combination with prior ES offers great promise as a commercial approach to beef chilling. Additionally, the shorter chilling time associated with rapid chilling provides an

opportunity to configure the chilling operation as a "line process". Line-chilling has traditionally been viewed as impractical for the simple reason that chilling tunnels long enough to handle the typical 24 h plus chilling times would be costly. However, as in most food-processing operations, continuous line processes are generally preferable (Drumm *et al.*, 1992a,b, 1989a,b; Joseph and McKenna, 1987). Possibly their greatest benefit is the capability of providing treatment consistency at each stage or point along the line. The consistency of a line process contrasts dramatically with the usual situation in conventional batch chilling rooms (i.e., "hot boxes") having variable thermal and moisture loads, untimely defrost events, non-uniform carcass distributions, and other problems that cause variable and unpredictable chilling. Also, conditions along a line process can be made to vary in such a way as to provide optimum chilling conditions. In comparison to the batch processing approach, the continuous (line) approach presents many more possibilities.

In summary, the optimum chilling technology would result in minimal shrink, reduced drip losses, reduced carcass handling and warehousing costs, and a lower potential for the proliferation of surface bacteria, extending shelf life and safety. The realization of these benefits is constrained by the need or desire to produce meat that has achieved its maximum potential eating quality, as reflected in desirable levels of fibre aging, sarcomere shortening, moisture retention, colour, and appearance.

To investigate the range of possible chilling regimes, a research chilling system with the capability of producing time-varying environmental conditions, such as might be

achieved in a continuous, rapid-chilling line operation is required. To provide reproducible and meaningful results, the system would need to be capable of chilling carcasses of differing size and shape so as to produce virtually identical carcass temperature histories. The design of such a system encompasses a number of design considerations, briefly discussed below.

Chiller design considerations

Air chilling of "hot" carcasses typically begins with a high energy demand that subsequently declines until thermal equilibrium between the carcass and the air environment is achieved. The initial high thermal load imposed by the hot carcass is augmented by high evaporative losses from the fresh carcass, which represents a substantial load in the form of latent heat as that moisture freezes onto the heat exchanger surface(es) (ASHRAE, 1986). Furthermore, some additional heat may be generated early in the chilling period by the postmortem anaerobic breakdown of muscle energy compounds (i.e., rigor processes). Thus, for a batch research chiller, the fundamental refrigeration capacity must be sized according to the peak chilling load that occurs early in the process, which may be twice as high as the average load over the entire process. Furthermore, sizing components for a conventional refrigeration circuit (i.e., vapour-liquid heat pump system) to match the peak load of a declining chilling-load requirement can result in reduced efficiencies, both in terms of equipment cost and the power used to run such a system. On the other hand, sizing equipment for the anticipated average load can result in greatly extended and unacceptable chilling times. Ideally, then, for a stationary chilling chamber that is not operated continuously between runs, the system

should have a reserve of chilling capacity (e.g., mass of pre-chilled refrigerant) that is accumulated prior to each batch run, and is sufficient to meet the deficit in chilling capacity of the driving refrigeration equipment during the early peak demand period.

With respect to the control requirements of the chiller, a single conventional vapour-liquid refrigeration circuit having a capacity to meet the peak load could be difficult to modulate during periods when the thermal load is substantially lower than the capacity of the system. Furthermore, since continuous chilling of large carcasses over an extended period (e.g., 12-24 h) is required, the usual periodic need to defrost heat exchanger surfaces also contributes to the control challenge. That is, for accurate control of carcass temperature decline rates, the system must have the ability to modulate environmental temperature over a wide range, while provision must be made for alternate chilling means during lengthy defrost events.

Finally, considerable variation amongst experimental carcasses in terms of factors that influence their individual rates of temperature decline during chilling can be expected. Examples include mass, shape, tissue composition, fat distribution, and surface fat thickness. To ensure that carcass temperature histories are similar within chilling treatments, the chilling system should, therefore, have the ability to effectively and directly control carcass temperature (i.e., temperature vs. time profiles), as opposed to simply controlling the surrounding environment.

Chapter II

OBJECTIVES

The two primary objectives of this study were (1) to investigate and characterize systems and conditions necessary for the establishment of alternative, well-defined beef temperature histories during postmortem chilling, and (2) to research the effects of alternative chilling regimes on meat quality, carcass hygiene, and moisture losses known to occur both during and after carcass chilling. Accomplishing these goals requires the development of a continuous, uninterrupted means of controlling transient postmortem temperatures of beef. An initial requirement was, therefore, to design, test, and evaluate a research chilling system having these features. Accordingly, the following design characteristics and evaluation criteria for the system were proposed:

(1) Ability to accurately control the average temperature of carcasses of widely varying heat transfer characteristics (e.g., mass, size, fat cover) along defined temperature-time paths;

(2) Refrigeration capacity equal to the peak initial thermal load imposed by the carcass mass to be chilled, and sufficient to chill 150 kg sides to $0^{o}C$ in less than 24 hours;

(3) Controls that permit automated system operation over a full 24-hour cycle;

(4) Automated means of defrosting heat exchanger surfaces to allow uninterrupted, continuous chilling throughout a 24-hour cycle;

(5) Responsiveness to any thermal load, or change in thermal load so as to minimize control error over a wide range of refrigeration conditions;

(6) Means to electronically monitor and log time-based data required for the assessment of chilling system performance, carcass responses, and actual process conditions.

Using such a system, the ultimate objective is to research the effects of arbitrary carcass temperature histories of possible commercial interest on meat quality, process hygiene, and carcass moisture losses. With these results, an optimum chilling regime might then be selected from amongst those investigated.

The quality of meat derived from electrically stimulated and experimentally chilled sides, representing aged prime beef of high commercial value was to be evaluated. In this regard, the general quality attributes of interest were: (1) meat toughness; (2) water holding capacity; (3) tenderness; and (4) meat colour. The primary goal with respect to meat quality was to determine whether muscle temperature history during chilling influences the ultimate quality of the meat after 5 days of aging in cold storage.

A further objective was to use mathematical models describing the temperature dependence of bacterial growth rate on meat surfaces (i.e., beef side) in association with processing data to predict and assess the potential for bacterial proliferation on freshly exposed, warm carcasses during chilling.

The final objectives were to measure carcass moisture losses of commercial significance that occur both within the chiller and during subsequent storage, and then to characterize and model the dynamics of the evaporation processes responsible for shrink.

Chapter III

MATERIALS AND METHODS

PART I. CHILLING SYSTEM DESIGN

A chilling system was designed with the capability of continuous operation despite the anticipated need to periodically eliminate frost from the heat exchanger surfaces used for air cooling. Furthermore, the system was designed to enable a wide range of cabinet air temperatures and to respond quickly to transient demands for lower air temperatures. A practical means for the system to be able to respond quickly or to meet unusually high chilling loads for a period of time was to create a reserve of pre-chilled refrigerant, and to provide sufficient heat transfer capability for that fluid to absorb sensible heat from the cabinet at the peak design rate. The need to provide heating to better control the cabinet environment was not evident for the transient chilling process. A mathematical computer model of the transient heat transfer elements of the system was prepared in the Mathcad (tm) programming language (version 5.0, Mathsoft Inc., Cambridge, MA) in order to size both the reserve capacity of chilling fluid and the required heat exchanger characteristics. That model is provided in Appendix I, and a description of the complete system as constructed is provided below.

Chilling cabinet

A previously constructed, insulated, stainless steel-lined cabinet in the Lacombe Research Centre abattoir was modified and used (Fig. 1). This cabinet, having internal

dimensions of 1.83 m width, 3.65 m height, and 1.83 m length, was fitted with an overhead carcass support rail connected to the abattoir rail system through a double-door opening. That rail was split into two terminating segments in a "Y" arrangement, such that two large, inverted carcass sides could be conventionally suspended adjacent to one another in the cabinet.

To achieve downward vertical air flow around the inverted carcass sides, a single rectangular air supply duct opening (ca. 1.6 m x 0.5 m) was created in the ceiling over the carcass support area. This opening was partially blocked by a 10 cm square rail support box-beam spanning the long axis of the opening directly beneath it. Turning vanes were installed in all of the supply ductwork bends, and a flow-straightening sheet-steel grid inserted in the opening, to assure uniform airflow distribution across the opening. To prevent short-cycling of air through the cabinet (i.e., inadequate movement of air over the carcasses), vertical return-air ducts with openings located at or below the lowest point on the suspended carcasses, 0.5 m above floor level, were constructed on opposite walls of the cabinet. Each of the two alternate centrifugal fans used for air circulation through the cabinet was capable of delivering 3.19 $m^3 s^{-1}$ of air with a maximum downward air velocity of about 4 m s^{-1} at the outlet.

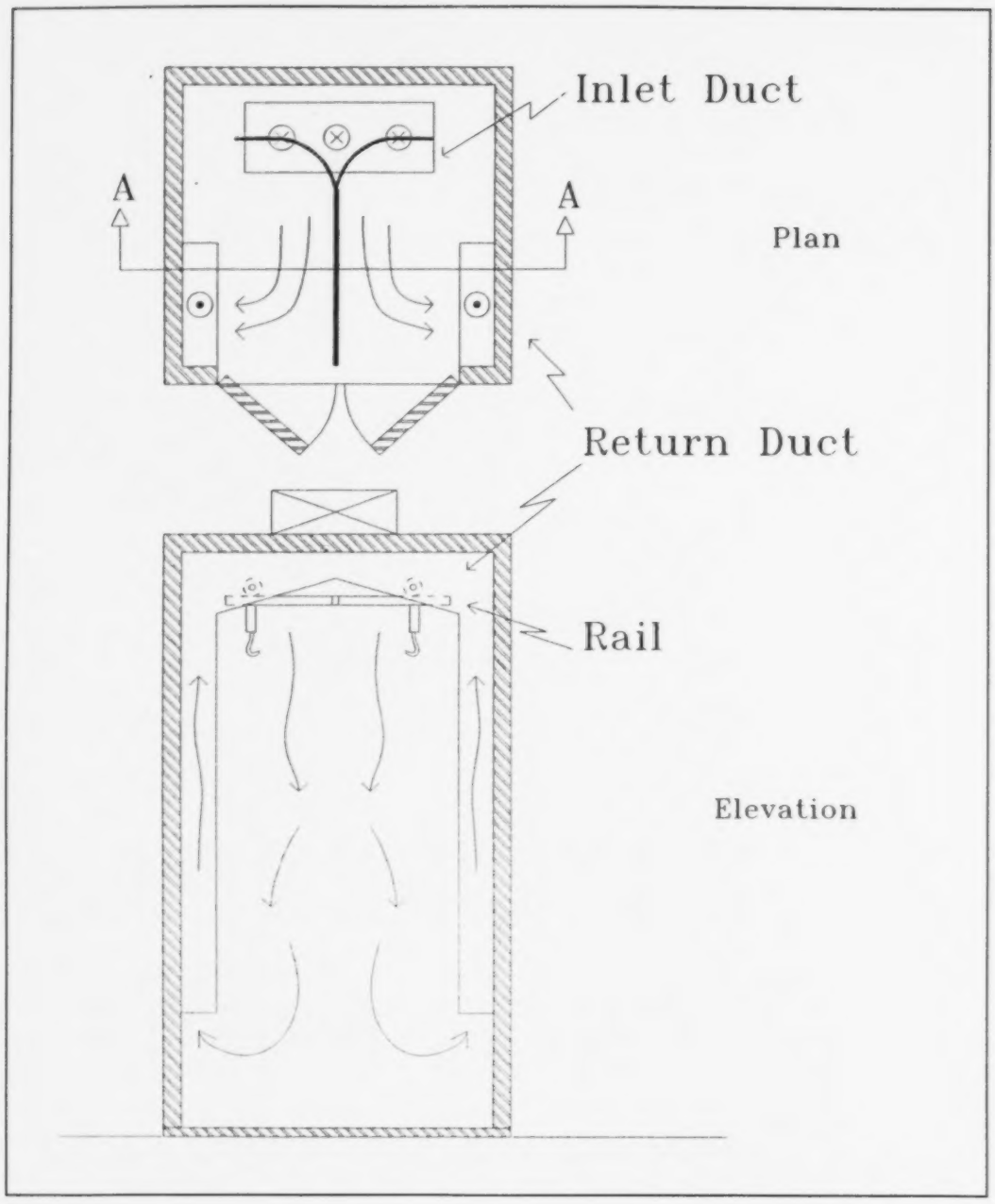

Figure 1. Plan and elevation views of chilling cabinet.

Refrigeration system

The refrigeration system for the chilling cabinet was developed to meet both the varying load requirements of the usual post-slaughter carcass chilling process and the need to accurately control and monitor the system for research purposes. A two-stage chilling system operating under combined programmable logic controller (PLC) and computer control was, therefore, developed. A schematic of the system is presented in Fig. 2. The first stage consists of a conventional R-22 refrigeration circuit (compressor 3DS3-1000 TFC, refrigeration unit CMDL-1000TFC001, Copeland Refrigeration Ltd., Brantford, ON). The first stage is used to chill approximately 2500 kg of an aqueous propylene glycol (PG) mixture containing 70% PG (mass basis) to a temperature of -30°C. The PG mixture serves as a refrigerant for direct air chilling and its temperature is thermostatically controlled to a pre-set value. The second stage consists of a pipe circuit through which the PG mixture is circulated and passed through one of two identical liquid/air heat exchangers (coolers) with centrifugal fans for forced-air circulation (HAP-111, Blanchard-Ness, Edmonton, AB). The flow of cold PG through these exchangers is controlled by 25.4 mm full-port electro-pneumatic on/off ball valves (Durco BFF1D4AO, operator: Automax S63SR10LTS, Duriron Co. Inc., Cincinnati, OH). These four valves are depicted in Fig. 2 (e.g., CVI1, CVO1).

Uninterrupted chilling is accomplished by alternating each exchanger between defrosting and chilling modes, with only one exchanger being used for chilling at any particular time. Defrosting is accomplished by circulating hot PG using a centrifugal

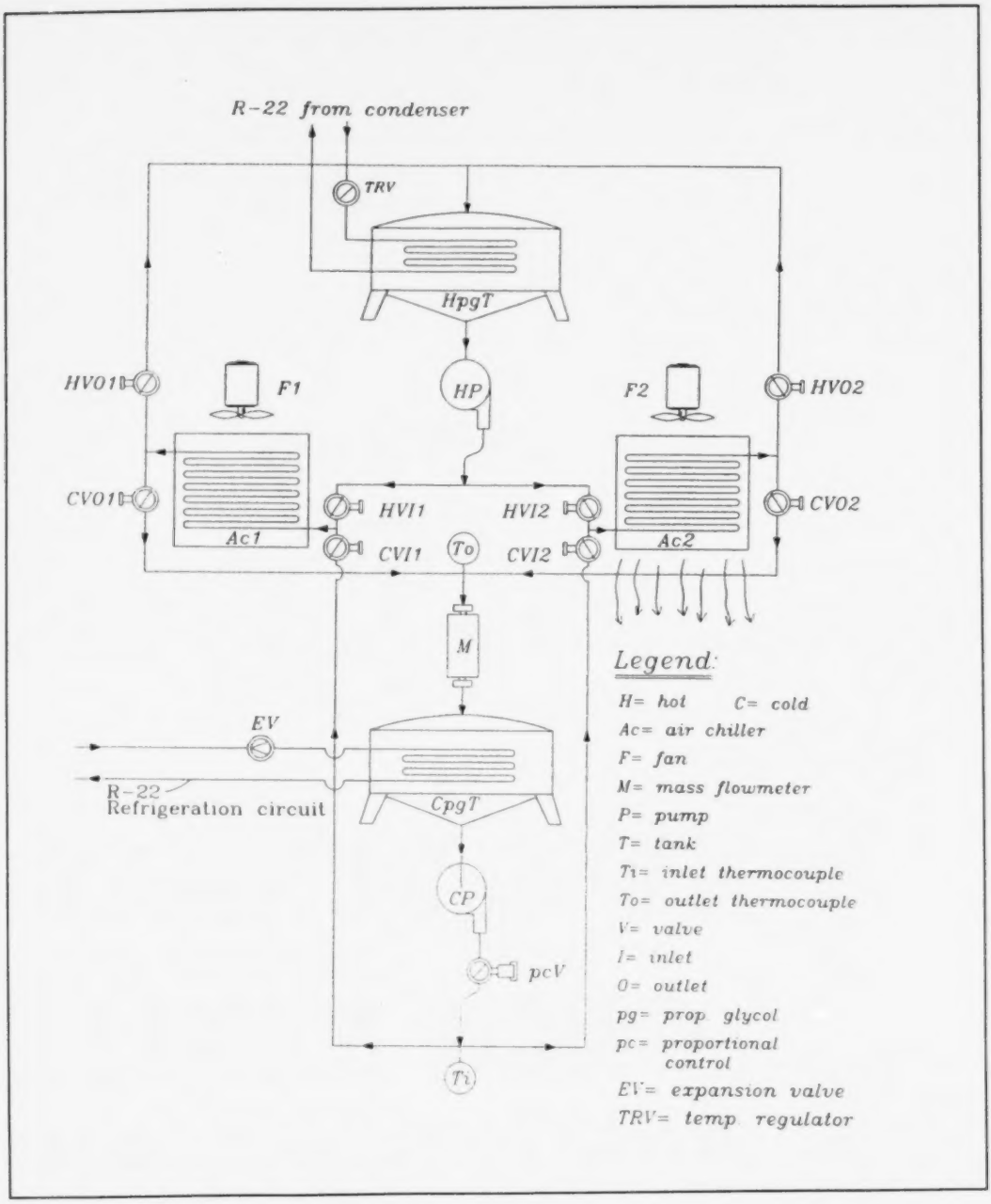

Figure 2. Schematic of chilling system showing primary control elements and chilling fluid circulation network.

pump (1ST1D100, Goulds Pump Co., Seneca Falls, NY) and the pneumatic control valves (e.g., HVI1, HVO1). The PG is heated in a supply tank by a heat exchanger containing hot, thermostatically controlled R-22 condensate. A rotary pump (HJ190, Viking Pump Co., Windsor, ON) is used to circulate the cold PG fluid. A rotary gear pump was selected to provide uniform flowrates despite the high variation in PG viscosity with temperature. Control of the PG flowrate is accomplished with an air-actuated proportional control valve (ball valve- Durco BFF1D4A0; operator- Automax S63SR10LTS; positioner - Automax H4000-237, Duriron Co., Inc., Cincinnati, OH; Fig. 2: Pcv) located downstream from the pump.

The sequence of events required for defrosting the operative heat exchanger (Fig. 3) is initiated when the air velocity is reduced to a pre-established value (e.g., 3.5 m s^{-1}). To ensure a smooth transition from one heat exchanger to the other, the alternate heat exchanger is pre-chilled by allowing half of the total PG flow to pass through it until its temperature is sufficiently reduced. When this has been achieved, the fan on the alternate heat exchanger is activated, and cold PG is fully routed through that exchanger. Simultaneously, the fan on the exchanger to be defrosted is turned off while hot PG is pumped through it for a period of about 5-10 minutes, as necessary.

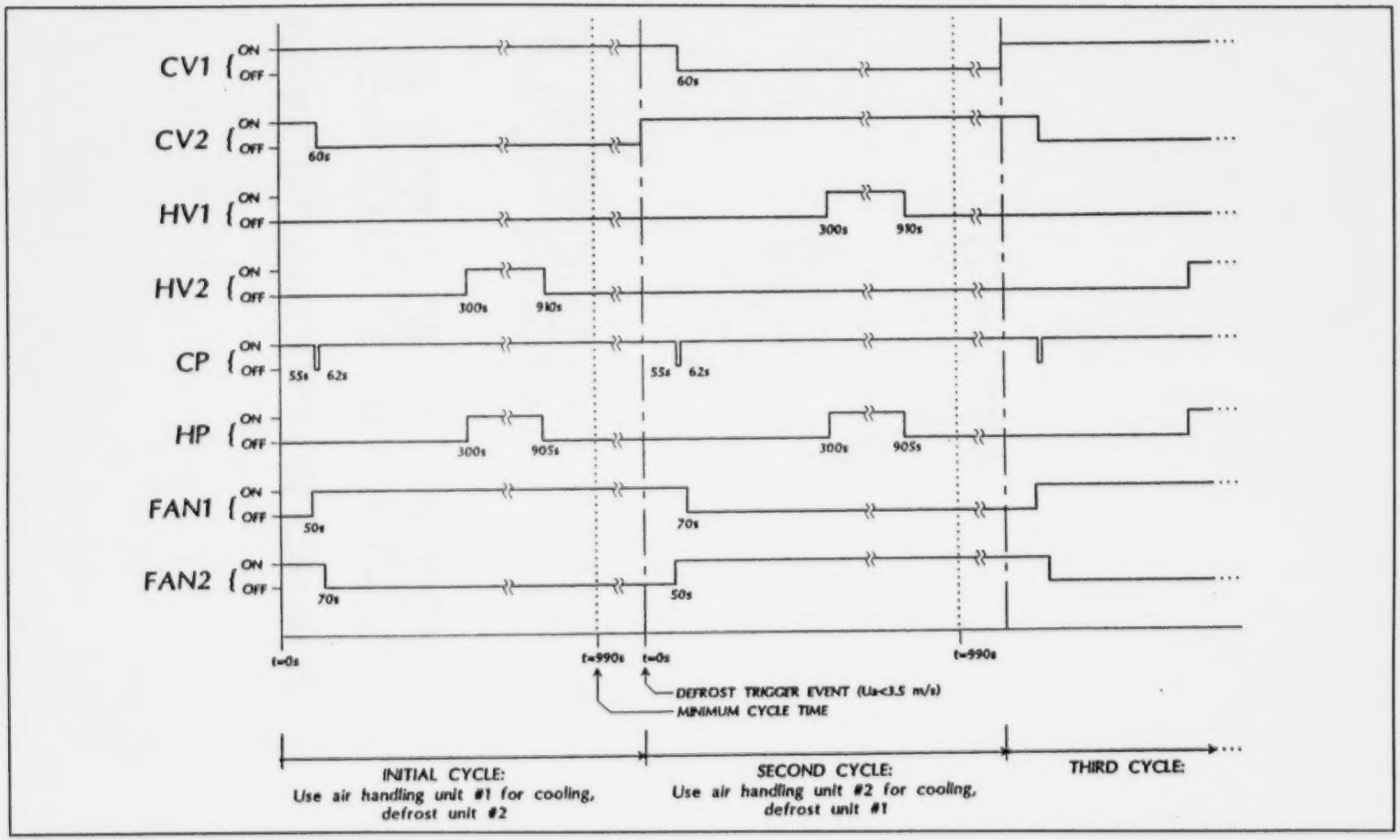

Figure 3. Sequence of control events for automated defrost of chilling system heat exchangers.

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Control and data monitoring system

The primary controller for the second stage is a programmable logic controller (PLC; model 984-A120, Modicon Inc., Andover, MD) with plug-in circuits (modules) for multiple discrete inputs and outputs, resistance temperature detector (RTD) inputs, and analog input and output signals. An independent conventional thermostat interlocked with refrigeration circuit controls is used to control the R-22 refrigeration circuit, or first stage. This system reduces the cold PG reservoir temperature to a specified level, which may be as low as -30 °C. The control algorithm at the PLC level is implemented in advanced ladder logic programming language using software supplied by the PLC manufacturer (MODSOFT, v1.2, Modicon Inc., Andover, MD). A datalogger circuit board (OPTO 22/B2, Datatranslations, Temecula, CA) with a thermocouple input module (AD18T) and analog input/output module (PB16AH) is installed in the same enclosure with the PLC to permit additional monitoring, but is not used for control purposes. A remote microcomputer is linked via shielded communication cables to the datalogger and PLC systems for concurrent data recording and supervision of the control processes. These processes are mediated using network software (*In-Touch* version 4.10 development system, Wonderware Software Development Corp., Irvine, CA) and DDE[1] servers for the two communication systems (i.e., MODBUS plus, OPTO 22). A schematic of the overall control system is provided in Fig. 4.

[1] DDE denotes Direct Data Entry.

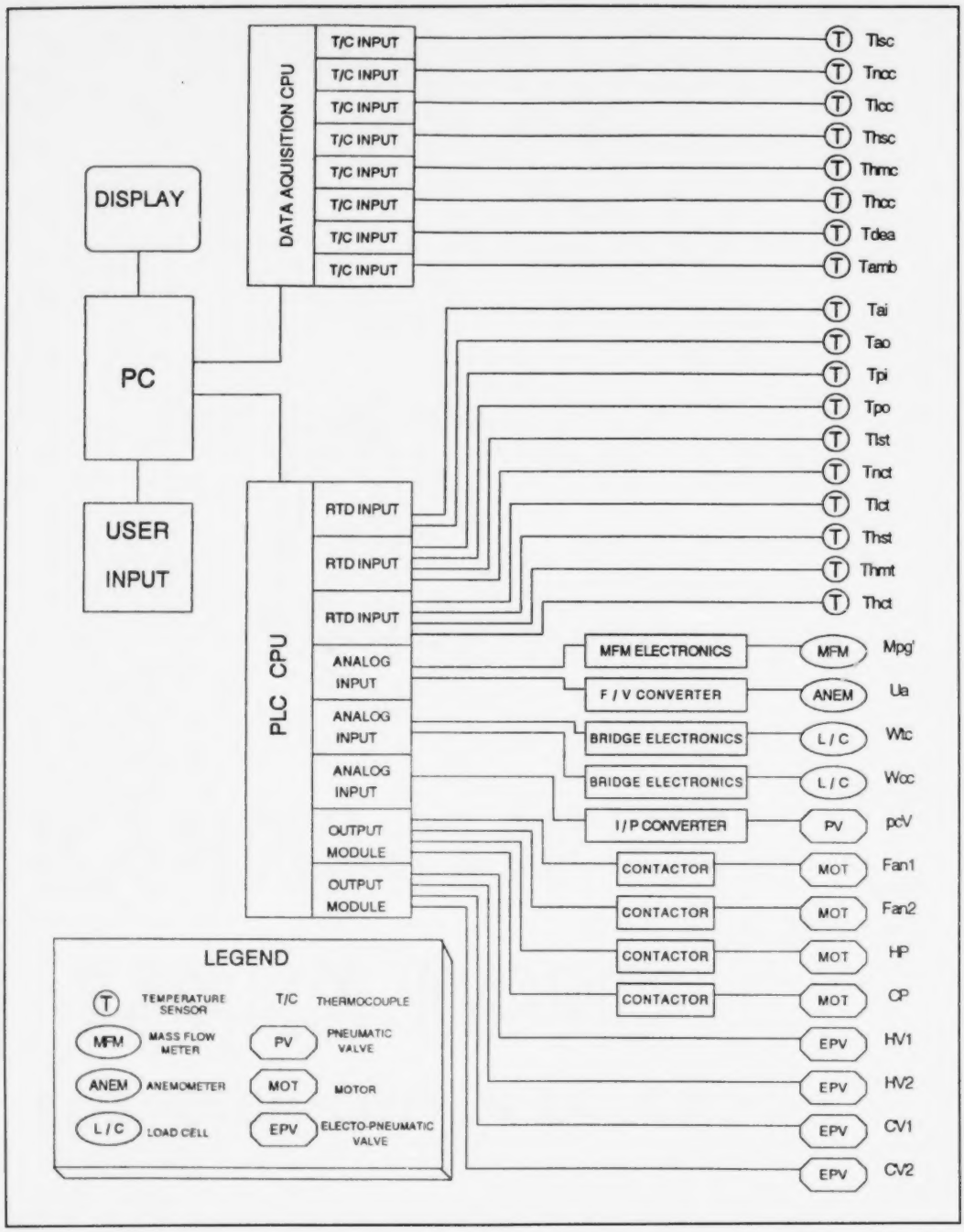

Figure 4. Simplified schematic of control system (3rd subscript in temperature nomenclature denotes either treatment (t) or control (c) carcass).

A computer graphical user interface model of the system, created with the *In-Touch* software, can be displayed on the computer monitor to allow manual or automatic control of the refrigeration processes through electronic mouse / monitor-icon interaction. Also, real-time observation of all sensor inputs processed by the PLC and datalogger is presented in graphical and numerical formats on the monitor under a series of computer windows. To help ensure the integrity of the recorded and/or manipulated data, all readings from sensors are scanned several times, checked for validity, and averaged for a specified time interval. This time interval is selected to provide the best response from the proportional-integral control function, and to be sufficiently short to allow accurate profiling of parameters as they change. A simplified flowchart outlining the logical operations carried out by the computer software is provided in Fig. 5.

Control algorithm

In Fig. 6 is a simplified flowchart of the PLC control algorithm for the second stage of the chilling system. The primary objective of the algorithm is to control the instantaneous rate at which the mass-average temperature of a single carcass side declines according to a programmed temperature versus time relationship. For purposes of discussion, the true mass-average carcass temperature is herein defined as[2]:

$$T_{ma} = \frac{\int_0^{Mc} T_m \cdot dm}{Mc} \qquad (1)$$

[2] See nomenclature table.

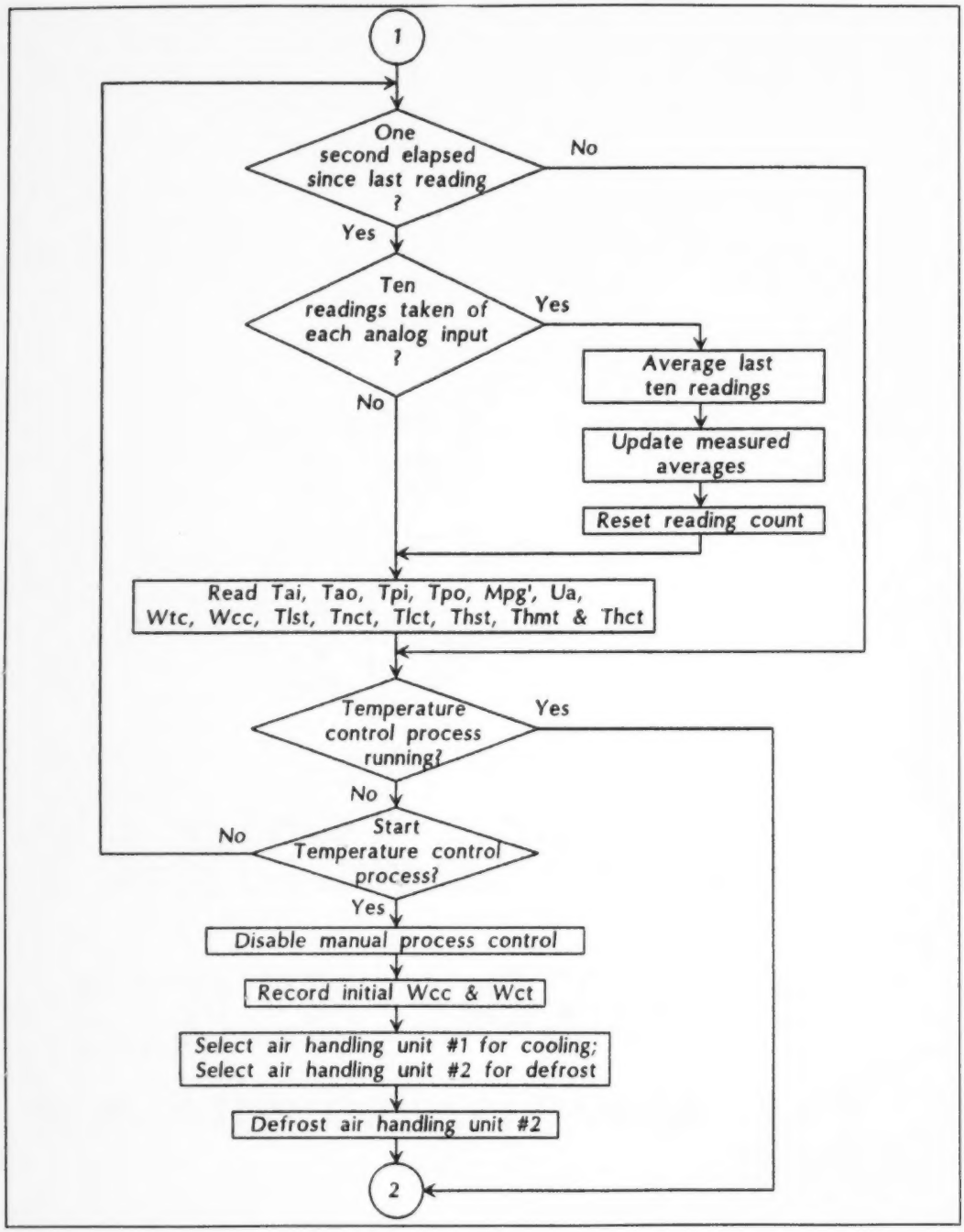
1
One second elapsed since last reading ?
No
Yes
Ten readings taken of each analog input ?
Yes
No
Average last ten readings
Update measured averages
Reset reading count
Read Tai, Tao, Tpi, Tpo, Mpg', Ua, Wtc, Wcc, Tlst, Tnct, Tlct, Thst, Thmt & Thct
Temperature control process running?
Yes
No
Start Temperature control process?
No
Yes
Disable manual process control
Record initial Wcc & Wct
Select air handling unit #1 for cooling; Select air handling unit #2 for defrost
Defrost air handling unit #2
2

Figure 5. Simplified flowchart of ladder-logic control algorithm for programmed chilling of beef sides.

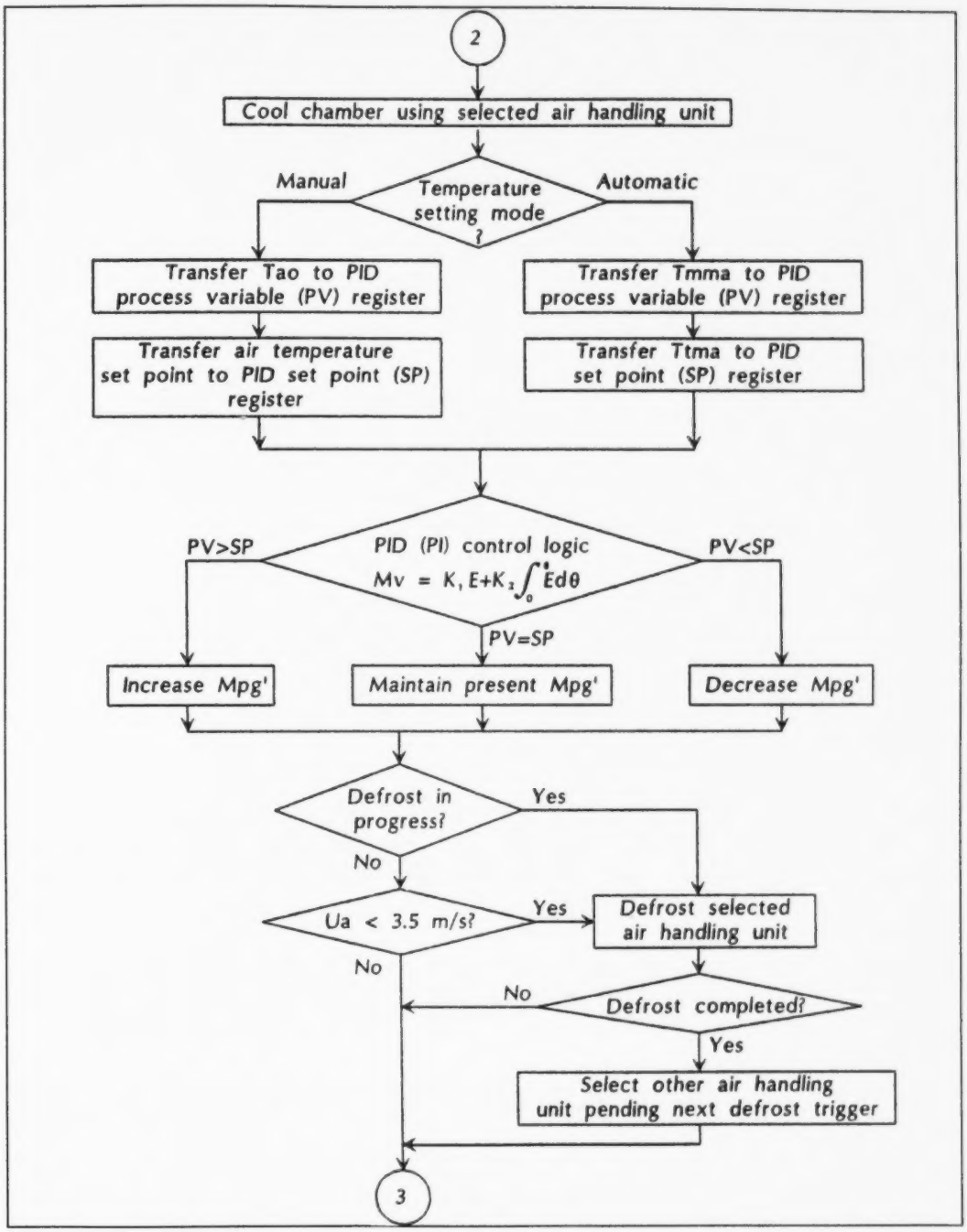

Figure 5. (Continued) Simplified flowchart of ladder-logic control algorithm for programmed chilling of beef sides.

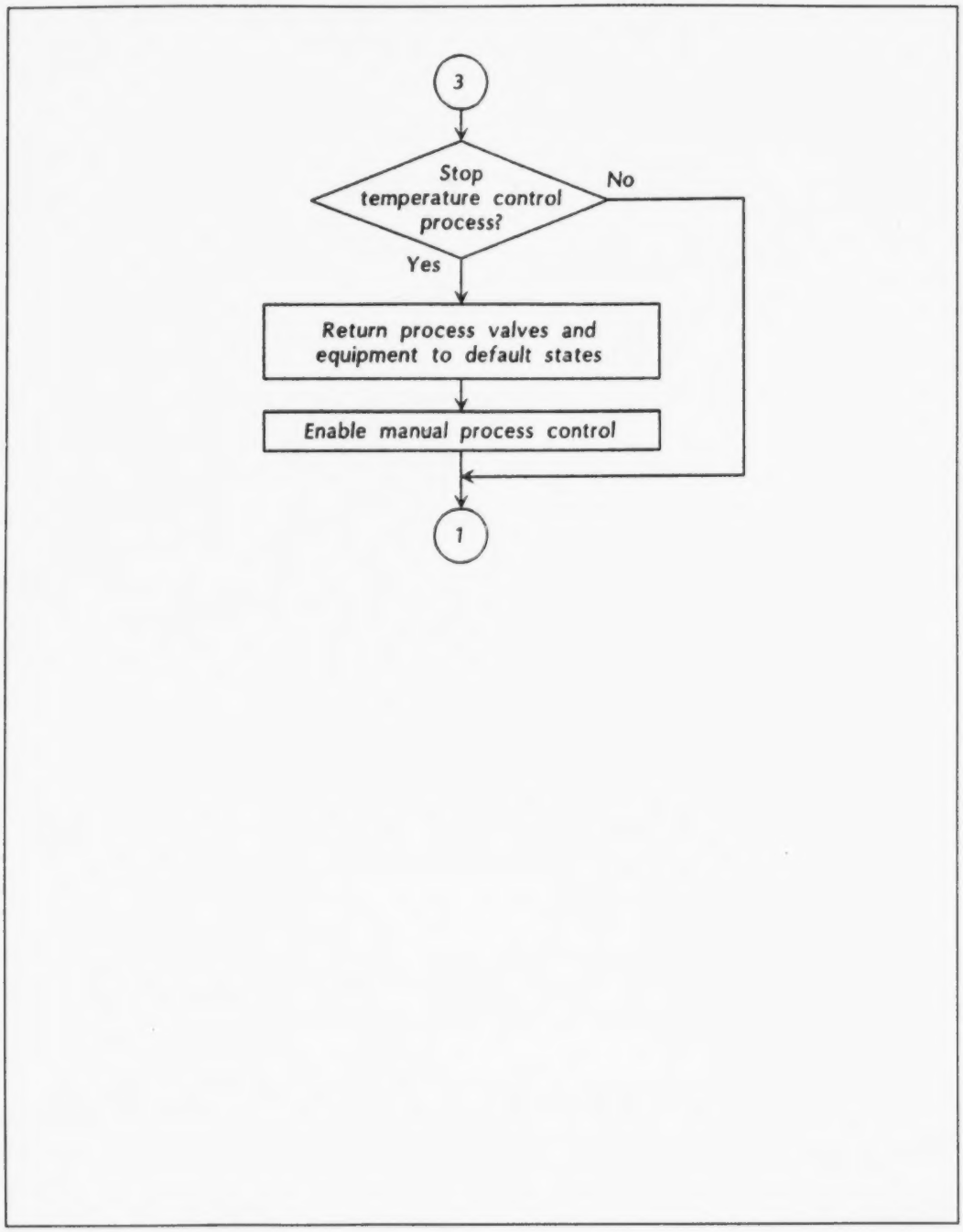

Figure 5. (Continued) Simplified flowchart of ladder-logic control algorithm for programmed chilling of beef sides.

Control is achieved by directly manipulating the cabinet air temperature through appropriate adjustments of the PG refrigerant mass flowrate. These adjustments are based on feedback of the calculated instantaneous error signal representing the difference between the actual and specified average carcass temperature during the course of chilling. The error value is transmitted to a PID[3] control routine embedded in the *Modsoft* ladder logic program, which in turn provides the necessary proportional plus integral adjustment of the PG flowrate.

In the absence of knowledge of the moment-to-moment temperature distribution of the beef side, the "measured" instantaneous carcass mass-average temperature could theoretically be estimated using a transient energy balance analysis of the controlled chilling cabinet system. That is, the energy decline of the beef side over any specified time increment $\Delta\theta$, as reflected in a drop in the value of Tma, is equal to the total of the thermal energy absorbed and/or released by the chilling system. Thus, for example, under steady-state conditions (i.e., neglecting air and cabinet temperature changes) the carcass mass average temperature decline over the short period $\Delta\theta$ could be estimated as:

$$\Delta T_{ma} = -\frac{\Delta\theta}{M_c \cdot C_c} \cdot \left[m_p \cdot C_p (T_{po} - T_{pi}) - Q_T + \frac{\Delta M_c \cdot \lambda_f}{\Delta\theta} \right] \qquad (2)$$

[3] PID denotes "Proportional + Integral + Derivative (derivative feedback was not applied).

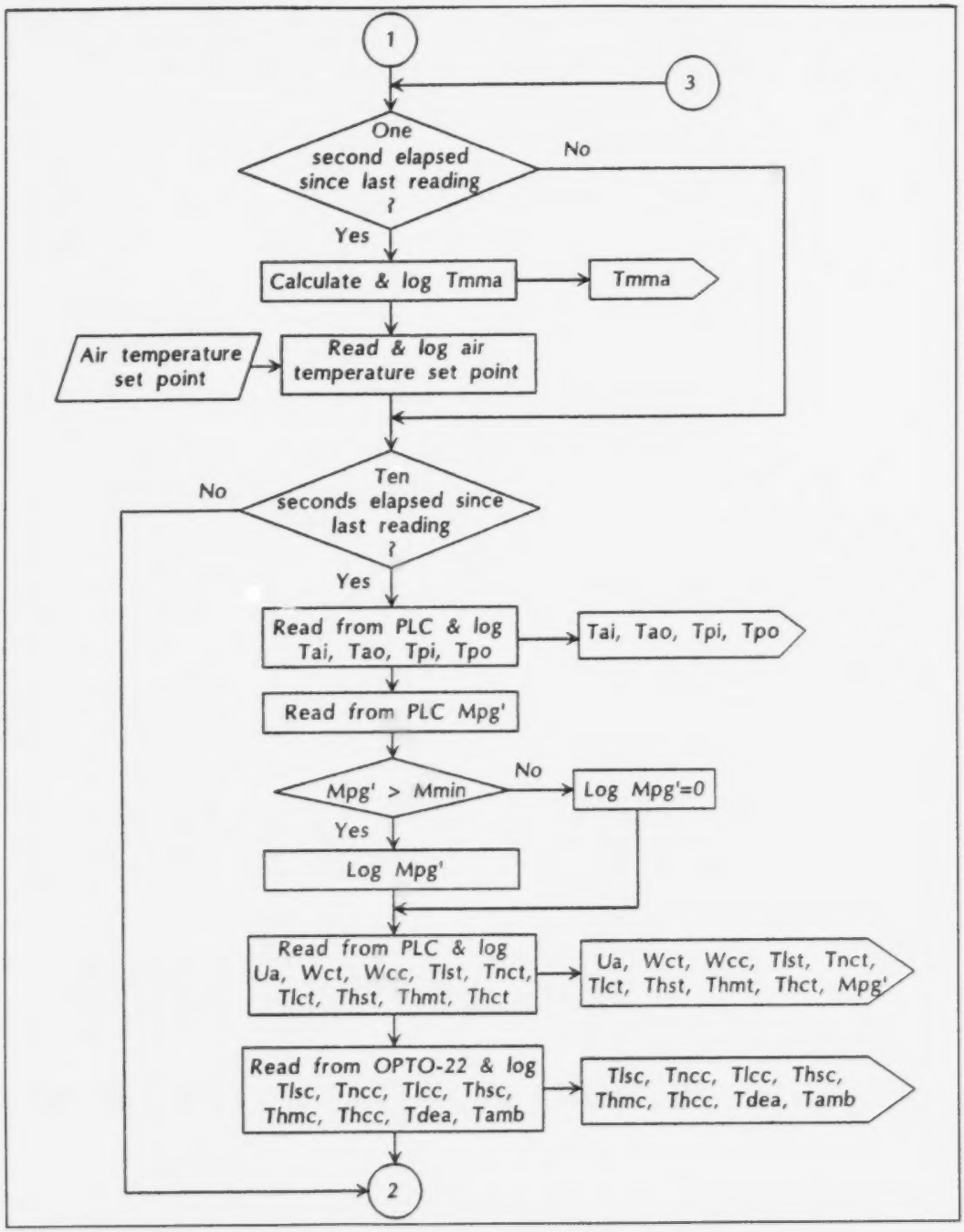
1
3
One second elapsed since last reading ?
No
Yes
Calculate & log Tmma
Tmma
Air temperature set point
Read & log air temperature set point
Ten seconds elapsed since last reading ?
No
Yes
Read from PLC & log Tai, Tao, Tpi, Tpo
Tai, Tao, Tpi, Tpo
Read from PLC Mpg'
Mpg' > Mmin
No
Log Mpg'=0
Yes
Log Mpg'
Read from PLC & log Ua, Wct, Wcc, Tlst, Tnct, Tlct, Thst, Thmt, Thct
Ua, Wct, Wcc, Tlst, Tnct, Tlct, Thst, Thmt, Thct, Mpg'
Read from OPTO-22 & log Tlsc, Tncc, Tlcc, Thsc, Thmc, Thcc, Tdea, Tamb
Tlsc, Tncc, Tlcc, Thsc, Thmc, Thcc, Tdea, Tamb
2

Figure 6. Simplified flowchart of algorithm for data monitoring, data collection, and supervision of PLC control processes.

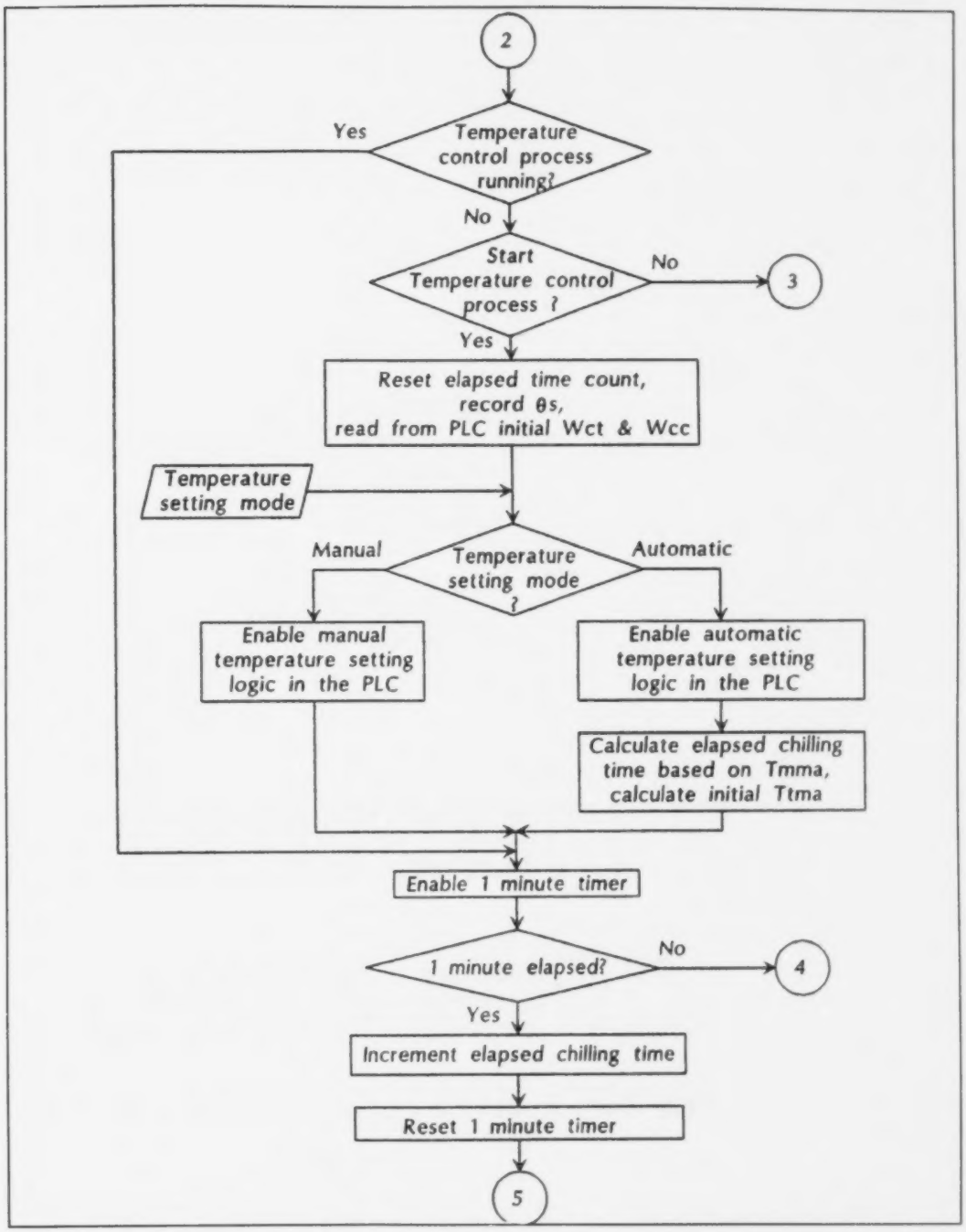

Figure 6. (Continued) Simplified flowchart of algorithm for data monitoring, data collection, and supervision of PLC control processes.

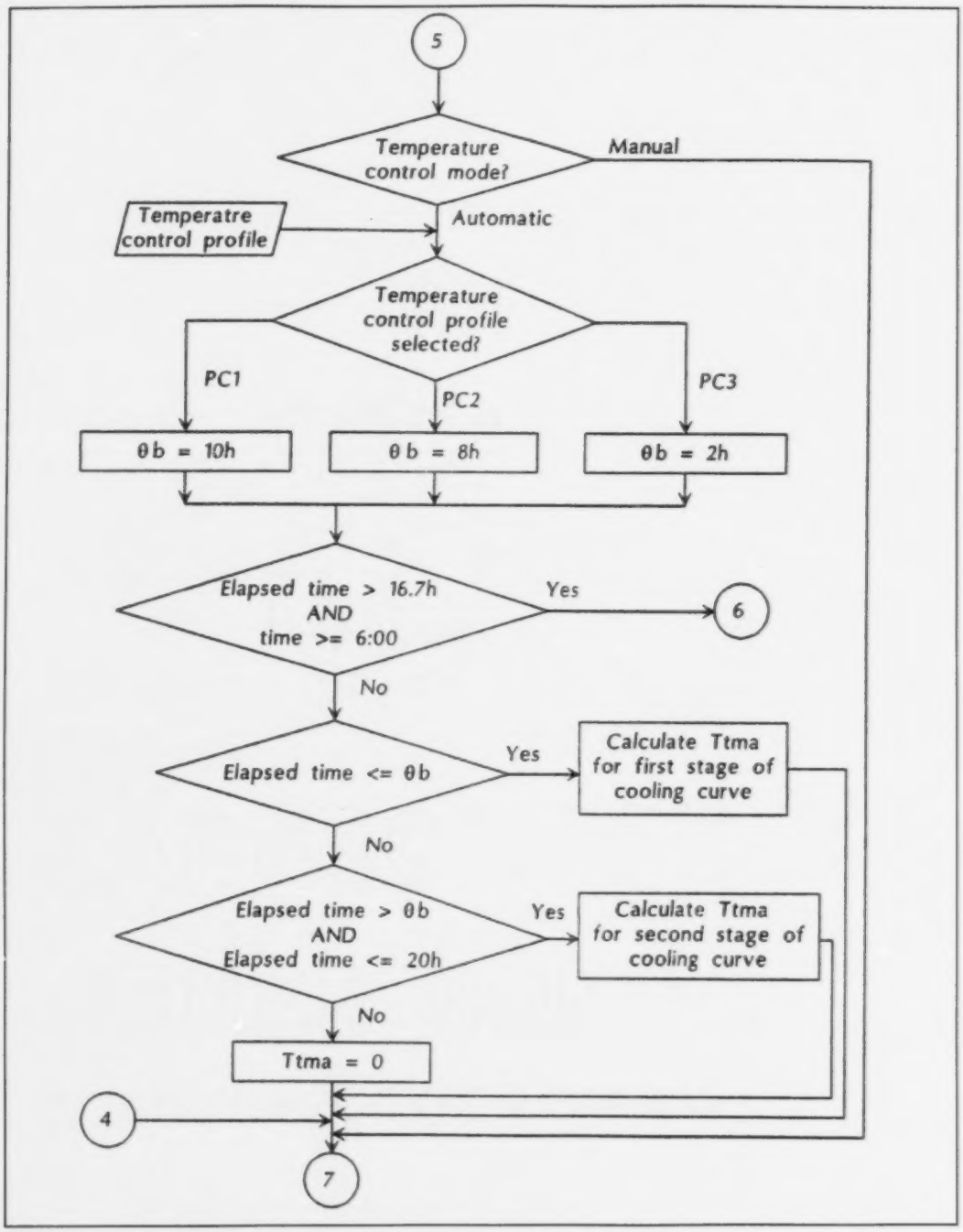

Figure 6. (Continued) Simplified flowchart of algorithm for data monitoring, data collection, and supervision of PLC control processes.

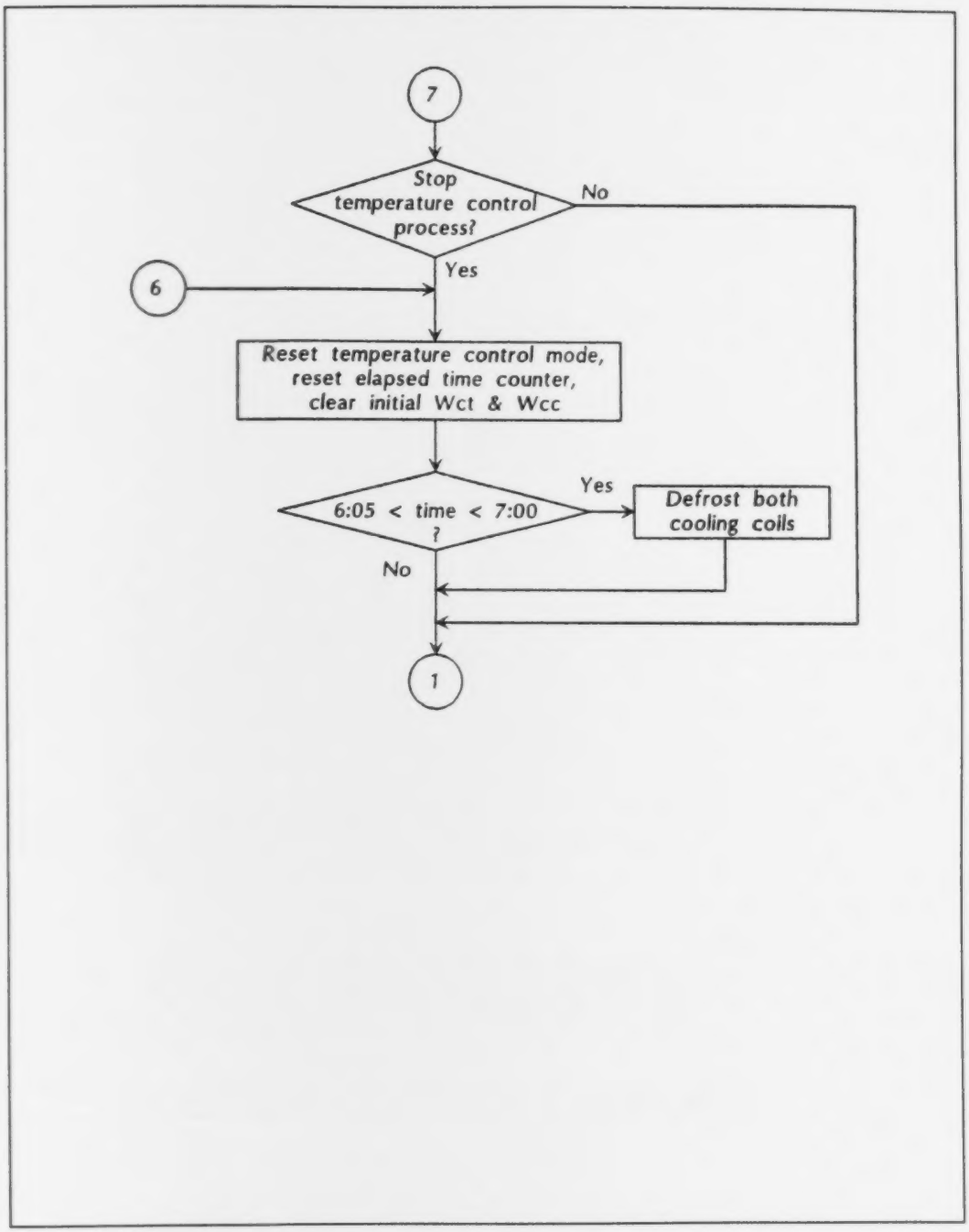

Figure 6. (Continued) Simplified flowchart of algorithm for data monitoring, data collection, and supervision of PLC control processes.

The total heat gain by the refrigeration system from external sources (Q_T) must also be calculated from information known about the system and its surroundings. From extensive calibration it was determined that the heat gains to the system were greater than the heat flux from the carcass, particularly during the latter stages of chilling. While it was possible to estimate Q_T from the monitored environmental and process conditions, it was believed that any error in that estimation would be too large for the purposes of estimating T_{ma} at all times.

Therefore, the control strategy used in the experiments reported herein was based on the direct electronic measurement of carcass temperatures and calculation of their average value as an estimate for T_{ma}. Taking this general approach can present a control problem of its own, in that the thermal responses to environmental change of the deep muscle tissues occur slowly, long after each control decision or action has been taken. In the absence of an accurate predictive model describing the expected response of the carcass to changes in the imposed environmental conditions (i.e., feed-forward control strategy), the precise control of deep muscle temperatures would be virtually impossible.

To overcome this problem, a simple strategy was devised in which a number beef side temperatures, including surface temperatures, were monitored (continuously measured) as a method for estimating T_{ma}. By including surface temperatures in the calculation of T_{ma} (estimate), a deviation from a new or given temperature (T_{ma}) setpoint during chilling would be quickly adjusted through changes to the average carcass surface temperature, which should respond quickly to changes in the air environment. It was

reasoned that consistent internal muscle temperature histories between carcasses and chilling runs would thus result. This follows from the fact that, for any two carcasses subjected to the same chilling program (in separate runs), the initially warmer carcass side would experience a compensating colder average surface temperature (or air temperature). After a period of time the temperature distribution differences between beef sides would tend to diminish despite differences in their initial internal temperatures, heat transfer characteristics, or both.

Moreover, it was reasoned that this strategy for controlling the *Tma* profiles would assure that each profile would be independent of carcass factors that influence overall rates of internal temperature decline, such that overall chilling times based on mass-average carcass temperatures would be identical for a given chilling program. In this regard, it was recognized that the *Tma* profiles to be investigated were developed from the anticipated response of a "mean" carcass, and that whilst chilling times and mass-average temperature profiles would be identical, carcass physical differences (e.g., carcass size, initial temperature, shape) were expected to be reflected in proportionate differences in internal temperature distributions, and in the environmental conditions developed by the controller in the chamber at any instant in time.

PART II. EXPERIMENTAL

Chilling treatment programs

Experiments were carried out to evaluate the ability of the chilling system to accurately control beef side temperature histories using the described system, and to evaluate the effects of three selected 20-hour chilling programs (Fig 7) on meat quality, hygienic efficiency, and carcass shrink. The experimental programs consisted of continuous, uninterrupted processes designed to provide specified average beef side temperature history profiles in the dressed sides beginning approximately 55 minutes after beef slaughter. The average side temperature was calculated from measured values obtained by continuous electronic measurements, as described below. The chilling processes were each automated to begin (i.e., $\theta = 0$) when the average beef side temperature had naturally declined, under abattoir conditions, to a value of 33.3°C. This was, approximately, the average temperature of beef sides shortly after trimming and rinsing using 40°C water. The delivered treatments were independent of carcass mass and composition, such that the chilling times, based on average carcass temperatures, were identical within each treatment by design. Moreover, the specified average side temperature was reduced to 0°C in 20 h for all three treatments, and held at this temperature thereafter. Opposite beef sides were simultaneously exposed to conventional chilling conditions in an air chiller (experimental control). In the conventional chilling process similarly suspended sides were exposed to downwardly moving air having a mean mid-carcass velocity of about 1 m s^{-1} and mean temperature of -1.2 °C.

Each of the target average carcass temperature (Tma^t) programs was determined as a separate function of time, each function establishing starting and ending temperatures of 33.3°C and 0°C, respectively. Thus, the only difference between treatments was the average carcass temperature history during the 20 hour processes. With the exception of a linear temperature decline phase in one program (PC1), the following general function was used to calculate the temperature decline curves of this study:

$$T_{ma}{}^{t} = T_i - \eta_1 \cdot \left[\theta + \frac{\eta_2}{\eta_1}\right]^{-1} + \eta_2 \cdot \left[\theta + \frac{\eta_2}{\eta_1}\right]^{-2} \tag{3}$$

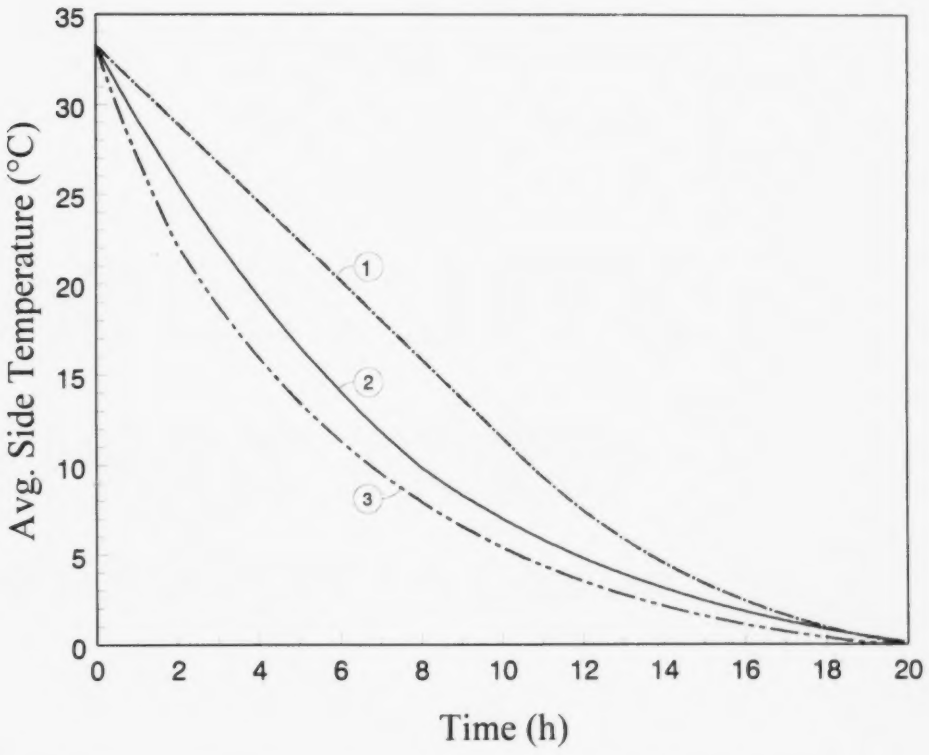

Figure 7. Target average carcass temperature-time profiles of the PC1, PC2 and PC3 programs.

The defining constants in Eq. (3) of the three experimental programs are given in Table 1, together with some of the important characteristics of these programs. The PC2 and PC3 programs were defined in two continuous phases as a programming convenience when minor changes to the programs were made (i.e., these programs could have been implemented in one phase).

Table 1. Constants used in Eq. (3) to define three experimental programmed chilling treatments, and distinguishing characteristics of these programs.

	PC1		PC2		PC3	
Parameter	**Phase 1**	**Phase 2**	**Phase 1**	**Phase 2**	**Phase 1**	**Phase 2**
Duration (h)	0-10	10-20	0-8	8-20	0-2	2-20
η_1 **(°C min)**	n/a	405900.23	393262.57	236348.51	164533.00	191858.96
η_2 **(°C min^2)**	n/a	609176960.5	928043024.4	414069356.8	199487288.3	296103523.0
T_i **(°C)**†	33.33	66.78	33.33	32.67	33.33	30.50
Max. Slope (°C h^{-1})	2.17	2.17	4.24	1.62	6.72	3.56

†T_i = Initial temperature in Eq. (3) (i.e., $T_{\theta=0}$)

The first programmed chilling treatment (PC1) consisted of an initial 10-hour phase during which Tma was reduced as a linear function of time, followed by a second 10-hour phase during which Tma was reduced asymptotically to a final temperature of 0°C (Fig. 7; $dT_{ma}/d\theta < 0$ when $\theta < 20$ h; $dT_{ma}/d\theta = 0$ when $\theta = 20$ h). During PC1

chilling, the carcass thermal energy content (sensible heat) declined at an ostensibly constant rate for the first 10 hours. Moreover, this was the only process to provide a sustained constant chilling rate during the important early period of chilling. For that extended first phase, neglecting factors such as changes in air velocity and evaporation rates, it was expected that the energy load on the refrigeration system would be virtually constant, and the difference between the average carcass surface temperature and the air environment temperature would likewise be virtually constant.

The second and third chilling programs (PC2; PC3) were progressively more severe in terms of their initial temperature decline rates. Nevertheless, these processes more closely resembled conventional chilling processes, in which the rate of heat transfer between the carcass and the surrounding air declines in an asymptotic fashion as the average temperature difference between the environment and carcass declines over time. These "declining rate" processes provided initially very rapid rates of temperature decline, followed by rates of steadily declining magnitude, which fell to zero in 20 hours.

For the three experimental treatments the controller was programmed to maintain the average carcass temperature at 0°C after 20 h of chilling, while all temperature and process conditions were monitored for an additional 2 hours. The temperatures of the selected muscle locations (below) were recorded over 22 h of chilling[4]. After 22 h sides were moved to a conventional holding cooler having a 24 h average air temperature of about -1.2 °C.

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[4] Programmed chilling treatments were of 20 h duration, but data logging continued for 22 h or more.

Temperature monitoring

Prior to each run, the experimental beef side was fitted with six probes (encased, 100 Ω, platinum RTD, Thermoelectric Co. Inc., Brampton, ON). Control sides were similarly fitted with six probes, each containing a thermocouple sensor (type-T, Alltemp Co., Edmonton, AB)[5]. All temperature sensors were sheathed in cylindrical, 3 mm diameter stainless steel bayonet-type probes of various lengths, with the sensing element sealed within the tip. These probes, in combination with the associated computer, PLC and data logging equipment, were used to continuously control (experimental program sides) and monitor (both sides) muscle temperatures in the hip, loin, and neck areas.

Prior to the running of experiments all temperature measurement systems were tested for stated accuracy by immersing all of the probe tips in both distilled, stirred ice water (0°C) and in constant-temperature, stirred water (ca. 40°C, 20°C) held in a temperature-controlled water bath. All such temperature readings were compared to those obtained using an accurate standard reference thermometer, simultaneoulsy held in the water at the same location. All temperature sensors were found to measure to within the accuracy reported by the manufacurers. Small (<0.25°C) temperature error corrections were subsequently applied in software.

Two probes were positioned in and over the *longissimus thoracis* (LT) muscle (loin); three were placed in or nearby the *semimembranosus* (SM) muscle (hip); and one probe was placed in the *serratus ventralis* (SV) muscle of the neck (Fig. 8). Of these, one

[5] Temperature sensors differed between control and treatment sides due to equipment availability.

probe each was used to measure the surface temperatures of the loin and hip. Surface probes were inserted parallel to the carcass surface within its fat layer, but allowing about 1 cm of the probe tip to emerge and become partially exposed to the air on one side.

The probe tips used for the loin were placed between the 12th and 13th rib. One LT sensor tip was positioned at the approximate geometric centre of a lateral cross-section of the loin (Fig. 8), and a second probe was placed on the surface with its tip positioned approximately 3 cm from the edge of the severed mid-plane, adjacent to the loin-centre probe tip.

Figure 9 shows the centre location of the temperature probe in the LT muscle. That probe was inserted to a depth, from the severed mid-plane cut, of 5.1 cm. Care was taken to ensure that the loin-centre probe was inserted perpendicular to the mid-plane cut of the beef side. Its penetration depth was selected to permit the probe tip to lie at the approximate geometric centre of the lean muscle area of a planar cross-section of the loin lying parallel to the ribs, visible in Fig. 9.

One of the temperature probes was positioned with its tip at the deepest hip location. That probe was inserted along a line perpendicular to, and extending from, the carcass longitudinal mid-plane cut. The insertion point for this probe was located 31 cm from the tail bone on a line bisecting the severed surface of the aitch bone. The deep-hip probe depth was determined by directly measuring the distance through the hip with a long probe, then inserting the shorter temperature probe half-way along the same path. The second probe-tip associated with the hip was positioned approximately 17 cm from

the mid-plane cut (horizontal surface line) on the fat layer of the upwardly facing external hip surface (inverted, vertically suspended side). That probe tip was positioned so as to be a minimum distance from that of the deep-hip probe. The third SM probe (mid-hip probe) tip location was precisely half way between the mid-plane cut and the deep-hip probe tip location. Finally, the SV probe-tip was also inserted to a depth of 5.1 cm below the mid-plane cut, adjacent to the 7th cervical vertebrae (Fig. 8). During each of the chilling programs, the instantaneous average carcass temperature, *Tma* , was computed as the average of the five LT and SM temperatures.

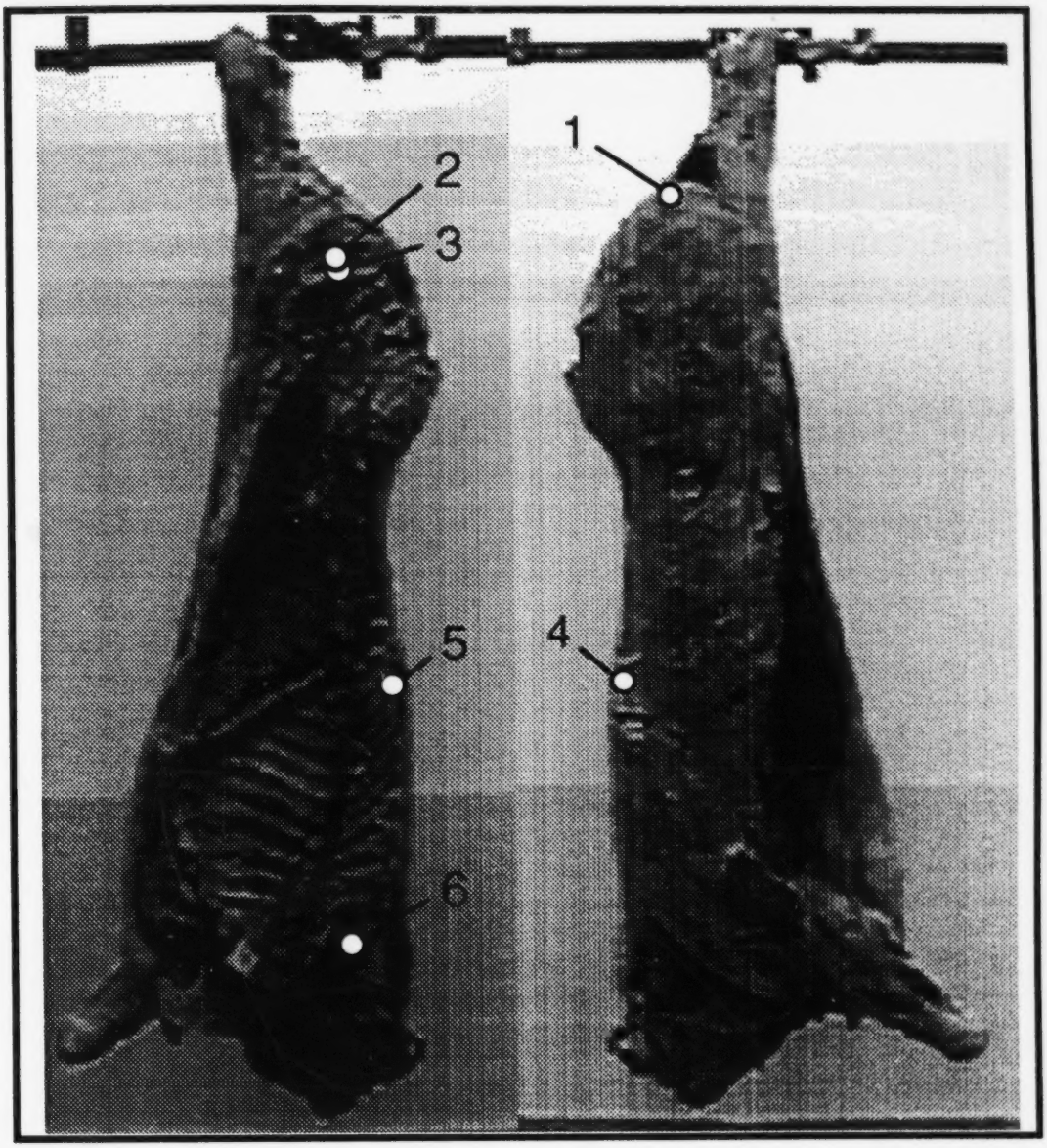

Figure 8. Temperature measurement locations on carcass sides:
1 - hip surface; 2- hip mid-depth; 3 - hip centre;
4 - loin surface; 5 - loin; 6 - neck.

Figure 9. Loin cross-section showing position of RTD sensor used to measure *LT* centre temperature.

Process monitoring

Twenty two process variables covering data for both the treatment and control chilling programs were simultaneously monitored and recorded during each run.[6] Twelve of these measurements were the carcass muscle temperatures described above (6 x control + treatment). Also monitored were the air temperature at the inlet and outlet locations of the controlled environment chamber, the propylene glycol temperatures within the inlet and outlet pipes leading to and from the operative air chiller, the ambient air temperature of the environment surrounding the controlled environment chamber, and the air temperature in the conventional chiller. As well, the carcass masses (both sides), the PG mass flowrate, and the air velocity at the duct opening above the suspended beef side in the controlled environment chamber, were electronically monitored and recorded.

The PG mass flowrate was monitored with a fixed-position, non-interfering mass flowmeter (model D-100, Micro Motion, Boulder, CO). The mass of each side was monitored using a load sensor (model LCCB-1K, Omega Engineering, Stamford, CT) connected to an input module of the PLC. Air velocity in the controlled chiller was monitored using a telescoping vane-type anemometer (model 228-MS, Solomat Instrumentation, Stamford, CT), also connected to the PLC.

Air velocity in the conventional chiller was not monitored, but was spot-measured at random times and at several locations about the circumference of the suspended side, at the 12th rib elevation using the same anemometer. All of the monitored data was

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[6] Tuesday runs did not necessarily include a control run.

subsequently reduced into 22-hour data sets for each run with measurements recorded at 5 minute intervals.

Beef sides were continuously weighed using a specially-manufactured support mechanism (Fig. 10) fitted with a 450 kg load cell (sensor model LCCB-1K; signal conditioner model DMD-466, Omega Engineering Inc., Stamford, CT). This was used primarily to determine the extent and timing of evaporative mass losses in the two chillers (experimental and conventional) under the different chilling programs. Using the abattoir weigh-scale (model H90-3004, Fairbanks Inc., St. Johnsbury, VT), both sides were again weighed at 24 and 144 h post-slaughter.

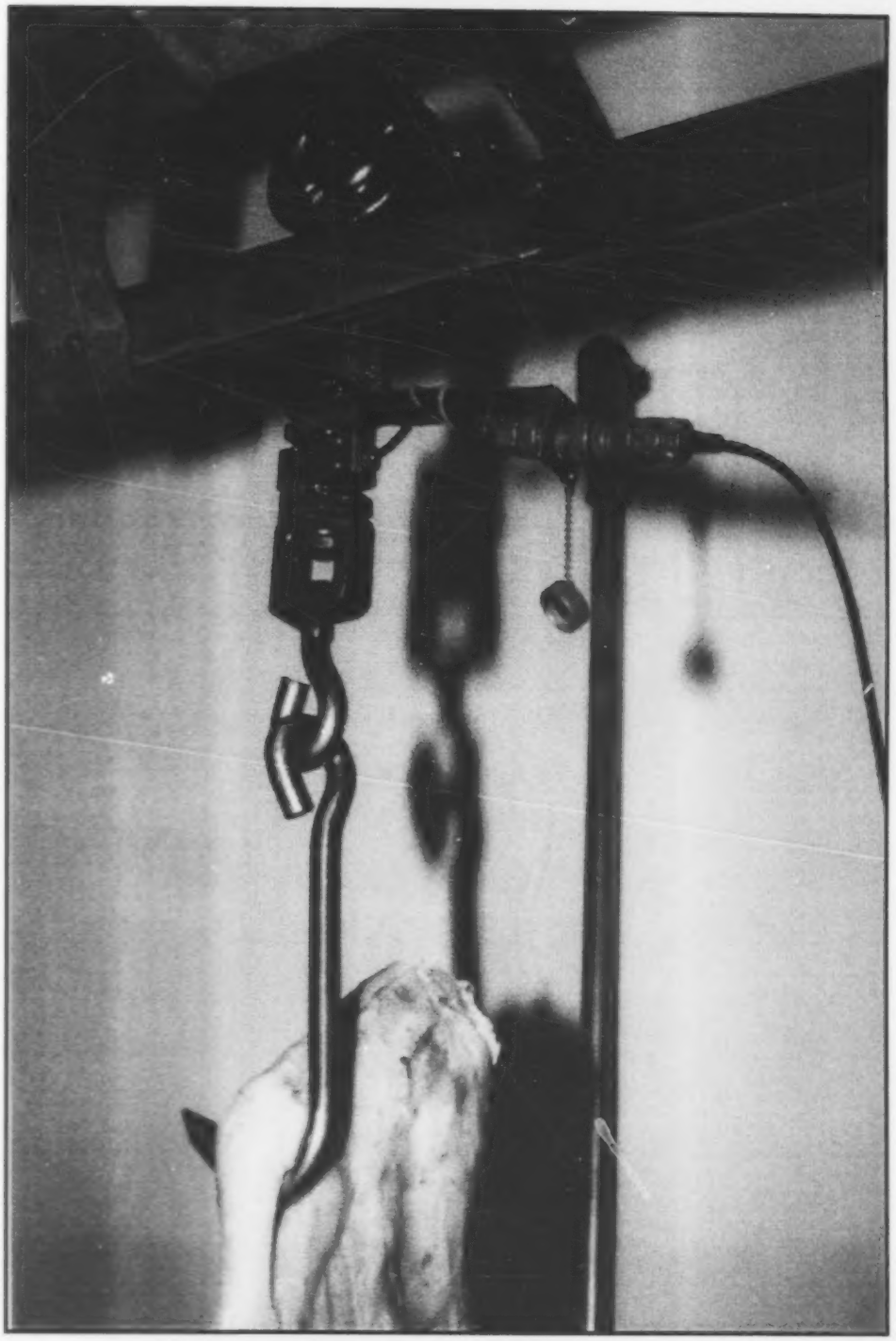

Figure 10. Support mechanism for continuous weighing of beef side during chilling.

Experimental design and schedule

Experiments were carried out using a split-plot design involving thirty-six animals, three chilling treatments, one conventional or control treatment and the two carcass halves. Hereford x Angus steers of between 17 and 19 months age at slaughter were individually assigned to one of the PC1, PC2, or PC3 programs. Opposing sides of the split carcasses were simultaneously chilled by the experimental and conventional (control) chilling processes, with equal numbers of right and left sides ultimately being processed under each chilling regime. Four animals were killed per week, Tuesday through Friday, over a nine week period. To reduce variation in carcass responses to the chilling regimes, the cattle were selected to minimize mass and back-fat variation. The average live-weight (mass) prior to the beginning of experiments (June 13) was 478.3 ± 22.8[(7)] kg and the average live-weight at slaughter was 510.9 ± 17.4[(6)] kg. Back-fat measured at the 12th/13th rib location was determined by ultrasonic reflectance (camera model SSD-210DXII; probe-model UST-5021, AEC, Aloka Co. Ltd., Tokyo, Japan). The average back-fat thickness one week prior to the beginning of experiments was 6.0 ± 0.6[(6)] mm. To minimize mass variation amongst treatments, twelve progressive mass groups of 3 animals each were established, these consisting of animals of most-similar mass. These groups were ranked in descending order of mass, and each animal within each group was randomly assigned to one of the three treatments (i.e., one treatment rep. per mass group). Random numbers were computer-generated by the spreadsheet program (Excel-5.0) used to create Table 2. Mass groups were processed

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[7] standard deviation

from heaviest to lightest to further reduce overall mass variation (this reduced the standard deviation in live-weight from a pre-experiment herd value of 22.8 kg to a kill-day value of 17.7 kg). To eliminate possible "day-of-week" effects, the sequence of processing treatments was ordered so as to assign equal numbers of each treatment to each of the four scheduled process days. Within each mass group either all right sides or all left sides were assigned to the experimental or control groups, with the assigned side alternating between consecutive mass groups (Table 2).

Table 2. Experimental design and schedule with live animal data[‡].

Week Number	Run Set	Date 1994	Day No.	Random No.	Calf I.D.	Live Mass (kg)	Back Fat (mm)	Mass Rank	Chilling Program	Treatment Side
1	1	19-Jul	1	0.1565	310	528	6	1	PC2	R
1	1	20-Jul	2	0.7645	328	514	7	3	PC1	R
1	1	21-Jul	3	0.4447	345	522	7	2	PC3	R
1	2	22-Jul	4	0.2437	402	507	5	5	PC1	L
2	2	26-Jul	5	0.3745	415	505	6	6	PC3	L
2	2	27-Jul	6	0.1251	336	508	7	4	PC2	L
2	3	28-Jul	7	0.9846	410	498	6	9	PC2	R
2	3	29-Jul	8	0.9504	363	499	6	8	PC3	R
3	3	2-Aug	9	0.2847	409	502	5	7	PC1	R
3	4	3-Aug	10	0.4921	304	484	6	12	PC3	L
3	4	4-Aug	11	0.0217	365	493	7	10	PC1	L
3	4	5-Aug	12	0.1295	368	493	6	11	PC2	L
4	5	9-Aug	13	0.7612	397	482	7	15	PC1	R
4	5	10-Aug	14	0.3675	316	484	5	13	PC2	R
4	5	11-Aug	15	0.4439	399	484	5	14	PC3	R
4	6	12-Aug	16	0.0293	391	481	6	16	PC1	L
5	6	16-Aug	17	0.4283	335	480	7	17	PC2	L
5	6	17-Aug	18	0.8682	446	478	6	18	PC3	L
5	7	18-Aug	19	0.2304	396	477	6	19	PC1	R
5	7	19-Aug	20	0.8217	351	472	5	21	PC2	R
6	7	23-Aug	21	0.3424	374	476	6	20	PC3	R
6	8	24-Aug	22	0.8098	377	469	5	24	PC1	L
6	8	25-Aug	23	0.0784	366	470	7	22	PC2	L
6	8	26-Aug	24	0.4825	311	469	6	23	PC3	L
7	9	30-Aug	25	0.4745	411	468	6	25	PC3	R
7	9	31-Aug	26	0.8858	320	420	7	26	PC2	R
7	9	1-Sep	27	0.9915	348	431	5	27	PC1	R
7	10	2-Sep	28	0.6509	367	410	6	29	PC2	L
8	10	6-Sep	29	0.2559	313	460	6	28	PC1	L
8	10	7-Sep	30	0.6522	364	452	6	30	PC3	L
8	11	8-Sep	31	0.4482	421	449	6	32	PC3	R
8	11	9-Sep	32	0.3493	398	451	5	31	PC1	R
9	11	13-Sep	33	0.7462	344	448	5	33	PC2	R
9	12	14-Sep	34	0.8517	362	446	7	35	PC2	L
9	12	15-Sep	35	0.5570	355	447	5	34	PC1	L
9	12	16-Sep	36	0.9430	312	445	6	36	PC3	L

[‡] Data of June 13. Random numbers were used to assign animals within each mass group of 3 steers.

Pre-slaughter treatment of animals

The 36 Hereford-Angus steers were weaned in October, 1993, then placed in the Lacombe Research Centre feedlot on a diet of 60% grain and 40% silage until June 13, 1994. At that time, steers were placed on grass for one month and then finished on a diet of 15% grain and 85% silage in the feedlot. Steers were singly killed on consecutive kill-days over a nine week period beginning July 19. The day prior to its slaughter the designated steer was transported to the Lacombe Meat Research Centre abattoir at 3:00 PM where it was removed from feed and given free access to water. It was slaughtered at times ranging between 7:30 and 8:10 AM (mean stun time = 7:44 AM). At slaughter the steers were between 17 and 19 months in age and had an average live weight of 510.9 ± 17.4[8] kg.

Carcass preparation and handling

In the Lacombe Research Centre abattoir, animals were stunned (captive bolt), bled, skinned, eviscerated, split, trimmed and rinsed using conventional Canadian methods and equipment. The steer live-weight (kg) was measured, and the un-trimmed and trimmed dressed masses were taken and recorded for each side at 45 and 50 min postmortem, respectively. Electrical stimulation (ES; Electrical Stimulator, Koch-Britton Co., Kansas, MO) was applied to the side to be chilled in the computer-controlled chiller using a combination of 470 V, 60 Hz, 20 cycles/min for two consecutive periods of 1 min. The pH and temperature of the LT muscle between the 10th and 11th rib (dorsal side) at a depth of approximately 3 cm were recorded, after splitting and at 45 min

[8] standard deviation

postmortem. These measuremente were repeated directly after ES (treatment side only). The pH and temperature of muscle were measured using a portable pH/temperature meter equipped with a temperature sensing probe (model HI7667, Hanna Instruments, Woonsocket, RI), and pH spear-type electrode (Ingold Messtechnik AG, Urdorf, Switzerland). Care was exercised not to excessively disturb the fat layer surrounding the pH probe entry location, to avoid influencing localized heat transfer in the loin during chilling. Immediately following dressing and rinsing with 40 °C water, the two sides were moved to their respective chillers. The time between slaughter and the onset of chilling was 78.4 ± 9.8[9] min.

After 24 h, to avoid exposure of the sides to excessive and/or variable drying conditions during storage, sides were wrapped and sealed in a food-grade moisture barrier of 6 mil, cylindrical, polyethylene pinched closed at both ends (Fig. 11). Sealing of the bottom end of the barrier system was facilitated by a special heavy-plastic collar which supported a large plastic bag to capture drip losses. The sealed beef sides were held in a cooler maintained at a mean temperature of -1.2 °C, until the 6th day (approximately 144 h) postmortem.

[9] standard deviation.

Figure 11. Polyethylene film enclosure used to contain beef sides over 5 day holding period.

Grading and meat quality assessments

At the 144 hour post-dressing time, sides were again weighed. The loin was then broken at the 12th rib, commercially inspected and graded by Agriculture and Agri-Food Canada inspectors (Livestock Carcass Grading Regulations; Sept., 1993). The grading site was assessed for the following meat quality traits by trained personnel: fat cover (Fig. 12; mm; top, middle, and bottom), grade fat (mm), rib-eye width and length (scale 1-3), muscle score (scale 1-4), fat class (scale 1-9), cutability estimate (grade ruler: range 49-64), rib-eye area (grid-method; cm^2), yield grade (y1, y2, or y3), and subjective marbling score (devoid=100, practically devoid=200, traces=300, slight=400, small=500, modest=600, moderate=700, slightly abundant=800, moderately abundant=900, abundant=1000).

After 20 minutes had elapsed from the time the each rib-eye became exposed, meat colour was determined using a reflectance-type analytical camera (Chroma Meter II, Minolta Camera Co., Osaka, Japan) providing output values of the CIE[10] {L*, a*, b*} colour coordinate system. Three temperature and three pHu measurements were taken at a depth of about 3 cm., near the 10th rib, LT site used to measure pH and temperature at 45 min postmortem.

[10] CIE denotes Commission Internationale de l'Eclairage, 1976

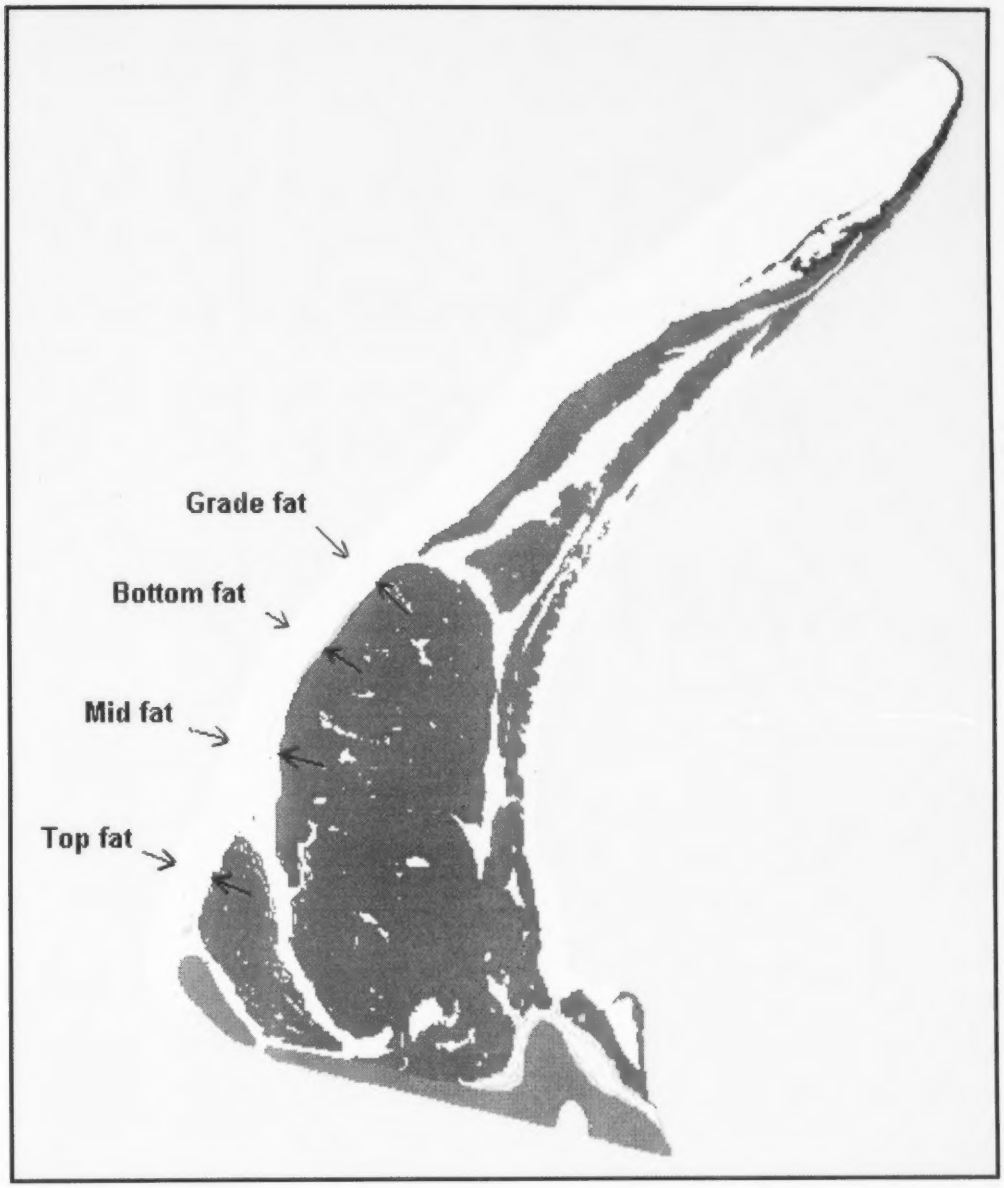

Figure 12. Schematic of measurement locations for subcutaneous rib-eye fat thickness.

Immediately after grading and rib-eye appraisal, rib-eye sample steaks were removed from the top of the 9th to the top of the 12th rib, for objective quality assessments. A 2 mm thin slice was taken from the 12th rib end for sarcomere length, fibre width, and myofibril fragmentation index (MFI) determinations. A 25 mm thick steak was cut and weighed on a pre-weighed Styrofoam steak tray for drip loss determination (Kauffman *et al.*, 1986). A 40 mm thick steak was removed, vacuum packaged, then frozen and stored at -40 °C in preparation for subsequent force-deformation analysis (i.e., shear cell stress/strain). A further rib sample for soluble protein determination was removed, trimmed of visible fat and tendon, and twice ground through an auger-type grinder fitted with an extrusion plate having pores of 3 mm, then frozen and stored at -40°C for subsequent analysis.

LT muscle sarcomere length and fibre width were determined by the method described by Jeremiah *et al.* (1985) using a light microscope fitted with a vernier adjustable cross-hair ruler. Twenty replicate measurements of the sarcomere length, and ten replicates of the fibre width were taken for each sample.

The myofibrillar fragmentation index (MFI) was determined by a variation of the method of Davis *et al.* (1980). Accurately weighed 5 g samples (± 0.005 g) from the centre of the rib-eye sample steak were finely minced with a sharp knife and then homogenized with 50 mL of aqueous solution (0.25 M Sucrose, 20 mM NaCl, 5mM EDTA) in a Waring blender (model 31BL92) at low speed for 45 s. The resulting slurry was thoroughly filtered through a 0.25 μm pre-weighed mesh screen (approx. 25 cm^2).

The screen was blotted three times under firm pressure using dry filter paper to remove unbound liquid and left to dry under ambient laboratory conditions (18-20 °C) for 24 h, weighing at 40 min and 24 h. Forty-minute and twenty four-hour MFI values were expressed as the residue percentage of the original 5 g sample.

Protein solubility (mg g^{-1}) was determined by the method of Barton-Gade (1985). Frozen, 2.00 g samples were thawed at 4 °C overnight and homogenized at 5000 rpm (Kinematica PT 10-35 homogenizer with P-20 generator (mixing head), Brinkman Instruments Ltd., Mississauga, ON) in 1.1 *M* KI, 0.1 *M* phosphate buffer having pH 7.4. Samples were then incubated overnight (2 to 4 °C) and filtered through coarse filter paper. One hour after the start of filtration, 2 mL of the filtrate was transferred to an Erlenmeyer flask to which 50 mL of biuret reagent (distilled H_20; 5g of $C_4H_4KNaO_6 \cdot 4H_20$; 30 mL 10*N* KOH; 60 mL 4% $CuSO_4$; total volume = 2000 mL) was added. This mixture was allowed to stand for 1 hour, after which the extinction coefficient (550 nm) was determined using a colorimeter (PC800, Brinkman Instruments, Toronto, ON). The protein solubility in mg g^{-1} was calculated according to the method of Murray (1989).

Force and deformation response characteristics of cooked meat from the pre-frozen 40 mm rib-eye samples were measured using a force/deformation testing machine (model 4301, Automated Materials Testing System, Instron Corp., Canton, MA). Samples were prepared by thawing steaks overnight and cooking submerged in 80°C, 0.9% physiological saline until their centre temperatures reached 72°C, as determined by an accurate hand-held temperature probe. The steaks were then plunged into ice water

and cooled to about 4°C. A 19 mm diameter core sample was removed from the centre of the cooled steak, with the long axis of the core being roughly parallel to the grain of the meat sample at that location. With room conditions of 18°C and 70% RH, the core sample was then placed in a Warner-Bratzler thick-blade shear cell (model D372-19, Instron Corp., Canton, MA) and tested with the machine cross-head travel speed set at 50 mm min^{-1}. This was repeated three times for each steak sample. From the digitally recorded force versus displacement curves, the following characteristics were determined by the system software: (1) displacement at yield (zero slope); (2) load at yield; (3) displacement at maximum applied force; (4) maximum applied force; (5) input energy to attain first yield point; (6) input energy to attain breaking point; and (7) the best-fit positive slope of linear portion of force-displacement curve. Because two technicians were employed to carry out the series of measurements, and because of the sensitivity of meat sample traits to the preparation technique, the samples assigned to each technician were balanced amongst treatments to permit valid comparisons (it was later determined that the method used by each technician for core sample removal significantly influenced "shear value" results).

Prediction of bacterial growth

The proliferation or total number of bacterial cell divisions of a wild-type strain of *Escherichia coli* and a mixed population of different strains of *Pseudomonas* occurring on beef side surfaces over a defined chilling period was predicted using the approach of Gill *et al.* (1988, 1991a). Also, the proliferation of *Salmonella typhimurium* growing on either

lean or fatty meat surfaces was predicted using the same approach. The number of bacterial generations occurring in that time was evaluated by integration:

$$G = \int_{0}^{22} \Gamma[Ts(\theta)]d\theta \qquad (4)$$

A model giving the temperature dependence, over three closed temperature ranges (7°C ≤ Ts <30°C; 30°C ≤ Ts <40°C; 40°C ≤ Ts <47°C; with Γ=0 for Ts < 7°C), of the aerobic growth rate of *E. coli* growing in a half-strength Brain-Heart Infusion (Gill *et al.*, 1988) was used. This tri-phasic model was shown to predict bacterial population increases comparable to observed increases on meat surfaces (Gill *et al.*, 1988; Lowry *et al.*, 1988). Similarly, a bi-phasic model given by Greer *et al.* (1994) was used to predict growth rates of different strains of psychotrophic pseudomonads growing between temperatures of -2 and 35°C on meat and other media (model ranges: -2°C ≤ Ts <25°C; 25°C ≤ Ts <35°C; with Γ=0 for -2°C > Ts ≥35°C). Finally, exponential-decay equations developed by Dickson *et al.* (1992) giving the growth-rate of *S. typhimurium* on either lean or fatty beef surfaces under dynamic cooling conditions as functions of temperature over the 15 to 40°C range were used. The temperature dependence of *S. typhimurium* generation time at temperatures below 15°C was estimated from data published by Mackey *et al.* (1980) for *Salmonella* spp. Mackey's data was fitted to a 2-parameter, 6th order polynomial function of temperature and scaled to give a generation time at 15°C identical to the appropriate value given by Dickson *et al.* for growth on either lean or

fatty tissue, and a growth rate of zero was assumed for temperatures below 7°C. The various growth models are provided in Appendix II.

For purposes of comparison, the average surface temperature of each beef side, $T_S(\theta)$, was defined as the average of the hip and loin surface temperatures. Composite surface temperature histories for each chilling program were directly used in Eq. (4), which was solved by numerical integration (Euler method) using a 5 minute time increment. Furthermore, the mean standard error of each surface temperature history profile was determined over 22 hours, and that standard error was used to estimate experimental error in the prediction of bacterial proliferation associated with surface temperature history variation. In predicting bacterial growth on the carcass surfaces during chilling it was conservatively assumed that bacteria had previously undergone lag-phase development, and that, for purposes of comparison, all species were assumed to be in an active growing phase at the beginning of chilling. Computer spreadsheet (Mathcad) programs used to predict bacterial growth are provided in Appendix II.

Carcass moisture losses

The mass of each suspended beef side was continuously monitored and recorded at five minute increments. Evaporative losses (e.g., 1%) were small in comparison to the carcass masses (e.g., 250 kg) and the range of the load cell used (0-450 kg). For this reason it was necessary to smooth composite side mass histories using a logarithmic piece-wise smoothing (multi-step regression; Appendix IV) routine written in Mathcad (version 5.0, Mathsoft Inc., Cambridge, MA). The regression equations were

mathematically differentiated to yield evaporation rates as a function of time. The total mass loss as a percentage of the initial side mass occurring over the 20 h of chilling was defined as the shrink. The mass loss of shrouded, sealed beef sides that occurred over the five day period between the end of chilling and grading was defined as the carcass drip loss.

Moisture loss model

The influence of the time-dependent environmental and carcass conditions on evaporation rate was investigated through a modeling approach. In particular, the roles of the changing vapour pressure and temperature gradients within the chiller and between the carcass and the surrounding air stream were examined to determine whether the interaction of the average carcass temperature history and the environmental conditions created to achieve that history could have transient or net effects on evaporative mass losses during chilling. Other factors such as air velocity, carcass mass, and surface area were included in the model outlined below.

The evaporation rate can be evaluated as:

$$E = k_c' \cdot A_s \cdot (X_s - X_a) \tag{5}$$

where k_c' can be expressed in terms of the convective heat transfer coefficient h_c using the Chilton-Colburn analogy between surface heat and mass transfer, thus:

$$k_c' = \left(\frac{h_c}{C_p \cdot \rho}\right) \cdot \left(\frac{Pr}{Sc}\right)^{2/3} \tag{6}$$

For convective heat transfer around an immersed body (Geankoplis, 1994), the heat transfer coefficient may be estimated as:

$$h_c = \frac{1}{L_s} \cdot \beta \cdot k \cdot Re^{\alpha} \cdot Pr^{1/3} \tag{7}$$

Combining Eqs. (6) and (7) yields an expression for k_c':

$$k_c' = \frac{1}{L_s} \cdot D_l^{1/3} \cdot D_w^{2/3} \cdot \beta \cdot Re^{\alpha} \cdot Pr^{1/3} \tag{8}$$

Mathematical expressions to calculate the physical and psychrometric properties of air from the recorded environmental conditions were used in the evaporation rate model, and are summarized in Appendix III. The time-varying moisture concentration of air adjacent to the carcass surface, X_s, was calculated from the average surface temperature using the Antoine equation and the psychrometric relationship between vapour pressure and water concentration. Air directly adjacent to the carcass surface was assumed to be saturated, because the water activity of beef (post chilling) should be no less than 0.98 (Karel *et al.*, 1975), and because much of the carcass surface is fatty and hydrophobic. The moisture concentration of the air surrounding the carcass, X_a, was similarly calculated, based on the assumption that returning air in the cabinet air-inlet location (i.e., downstream from the refrigeration coil) was saturated.

The beef side surface area in Eq. (5) was estimated from the animal live mass using a correlation reported by McDonald *et al.* (1966) for live animal surface area:

$$A_a = \gamma \cdot W_l^{2/3} \tag{9}$$

Using this result, the side surface area was calculated as:

$$A_s = (1 - f_i) \cdot (1 + f_i) \cdot \gamma \cdot W_i^{2/3} \tag{10}$$

From grid measurements of a representative beef side, the value of f_i was estimated to be 0.732. Similarly, f_t was estimated to be 0.150. These ratios were assumed to be constant within the group of experimental animals used. The significant length dimension (L_s) in Eq. (7) was taken as the "equivalent length" of the beef carcass. A consistent method for determining L_s was developed by creating an imaginary "equivalent" beef side having the shape of a slab and having a mass W_s and area A_s. Therefore, L_s was calculated by:

$$L_s = \left[\frac{A_s}{2 \cdot \left(R_t \cdot R_w + R_t + R_w \right)} \right]^{1/2} \tag{11}$$

The terms R_t and R_w are, respectively, the ratios of the average side thickness and average side width relative to the average side length (L_s). The average width was determined from a series of equally spaced lateral, edge-to-edge measurements of a leg-suspended beef side in a side-view photograph (Fig. 8). The average length was similarly determined, using vertical measurements from the same photograph. It was assumed that all beef sides used in the study would share the dimensional characteristics R_w and R_t. From the need to satisfy volume and surface area equalities between the beef side and the slab, the ratio R_t was implicitly solved using the following equation:

$$\frac{V_s^2}{A_s^3} = \frac{(R_t \cdot R_w)^2}{8 \cdot (R_t \cdot R_w + R_t + R_w)^3} \tag{12}$$

where V_s, the beef side volume, is calculated from the known mass and average tissue density.

The values of α and β in Eqs. (7) and (8) were solved by fitting the model to the experimentally determined evaporation loss profile of each run using the estimated value of A_s and time functions of E, Re, Pr, X_s and X_a for that run (Appendix IV). Model parameter (α,β) solutions were obtained so as to predict the measured total evaporative moisture losses. Finally, the resulting model was used with the mean environmental histories associated with the three chilling programs as input to illustrate evaporation process dynamics during and under each of the chilling regimes.

Analyses of the data

The experimental process data sets, comprising the 22 monitored process variables recorded at 5 min intervals over 22 hours, were combined into appropriate electronic data sets and analyzed using programs (Appendix V) written in the Mathcad programming language (Mathcad 5.0, Mathsoft Inc., Cambridge, MA). Chilling times for each of the six muscle locations to decline to 10 and 0 °C were determined from the experimental temperature histories by scanning (to bracket the desired result) followed by linear interpolation of the bracketed five minute data interval. Logarithmic curve smoothing routines were also written and used to estimate values and time derivative profiles, where appropriate. A Student t-analysis routine was written in Mathcad and

used for the purpose of analyzing point-by-point differences between muscle temperature profiles. Paired t-test analyses to determine the significance of differences in chilling times were carried out using the Statistical Analysis System (SAS) General Linear Models (GLM) software procedure (Version 6.10, SAS Institute., Inc., Cary, NC).

The meat quality data were organized and analyzed using computer procedures of the SAS software (Appendix VI). The primary effects of the experimental treatments on all of the quality attributes were investigated by standard analysis of variance (ANOVA) methodology using SAS GLM procedures. In separate ANOVAs, the effects of chilling treatments on objective and subjective quality attributes were compared amongst treatments, as well as between each treatment and its experimental control. Comparison of results among the treatments were analyzed according to the following symbolic ANOVA model:

$$Y_{j(i,k)} = S_i + R_{j(i)} + T_k + (ST)_{i,k} + E_{j(i,k)}$$

Where:

Y = Experimental result
S = Side (left vs right) effect.
ST= Side x Treatment interaction effect.
R = Replication effect.
T = Treatment effect (PC1, PC2, PC3)
E = Unexplained variation (error).
$i = 1,....2;\ j = 1,....6;\ k = 1,...3.$

Comparisons of results between each experimental treatment and its control were analyzed according to:

$$Y_{j(i,k)} = C_i + R_{j(i)} + T_k + (CT)_{i,k} + E_{j(i,k)}$$

Where:

Y = Experimental result.
C = Control-Side (left vs right) effect.
CT= Control-Side x Treatment interaction effect.
R = Replication effect.
T = Treatment effect (e.g., PC1 vs. CON).
E = Unexplained variation (error).
i = 1,....2; j = 1,....6; k = 1,...2.

The effects of beef side (left vs. right) were tested against $R_{j(i)}$ in the above models. Possible interactions between chilling treatments and uncontrolled carcass characteristics (mass, fat cover) were investigated through analysis of co-variance (ANCOVA).

Chapter IV

RESULTS

PART I. CHILLING SYSTEM PERFORMANCE

The average propylene glycol and air temperature responses of the refrigeration system over the 20 hour chilling period of the three control programs are illustrated in Figs. 13, 14, and 15. These profiles illustrate the extent to which changes in the air and PG refrigerant temperatures were affected by the thermal demands imposed by each program. As expected, the chilling cabinet air temperature histories associated with each treatment program varied both with time and treatment program (Fig. 16a). The cabinet air temperature changed abruptly when the chilling program passed from phase 1 to phase 2 (i.e., at 10, 8, and 2 h for PC1, PC2 and PC3, respectively). However, these abrupt changes were not reflected in (measurable) sudden changes to the carcass surface temperatures, nor to the average carcass temperature. Also, the total thermal load imposed by the carcass side, chiller, and the surrounding environment caused the PG refrigerant flowrate to vary considerably with both time and treatment (Fig. 16b). A summary of chilling system performance attributes for the three processes during each of the two phases in each program is provided in Table 3.

While the air temperature histories for all three programs were uniquely different, the air temperatures consistently declined to a common value of -8.6°C after about 12 h. Subsequently, in the remaining 8 h, the minimum air temperatures (Table 3) for each process were attained. The minimum was lowest for the PC1 process

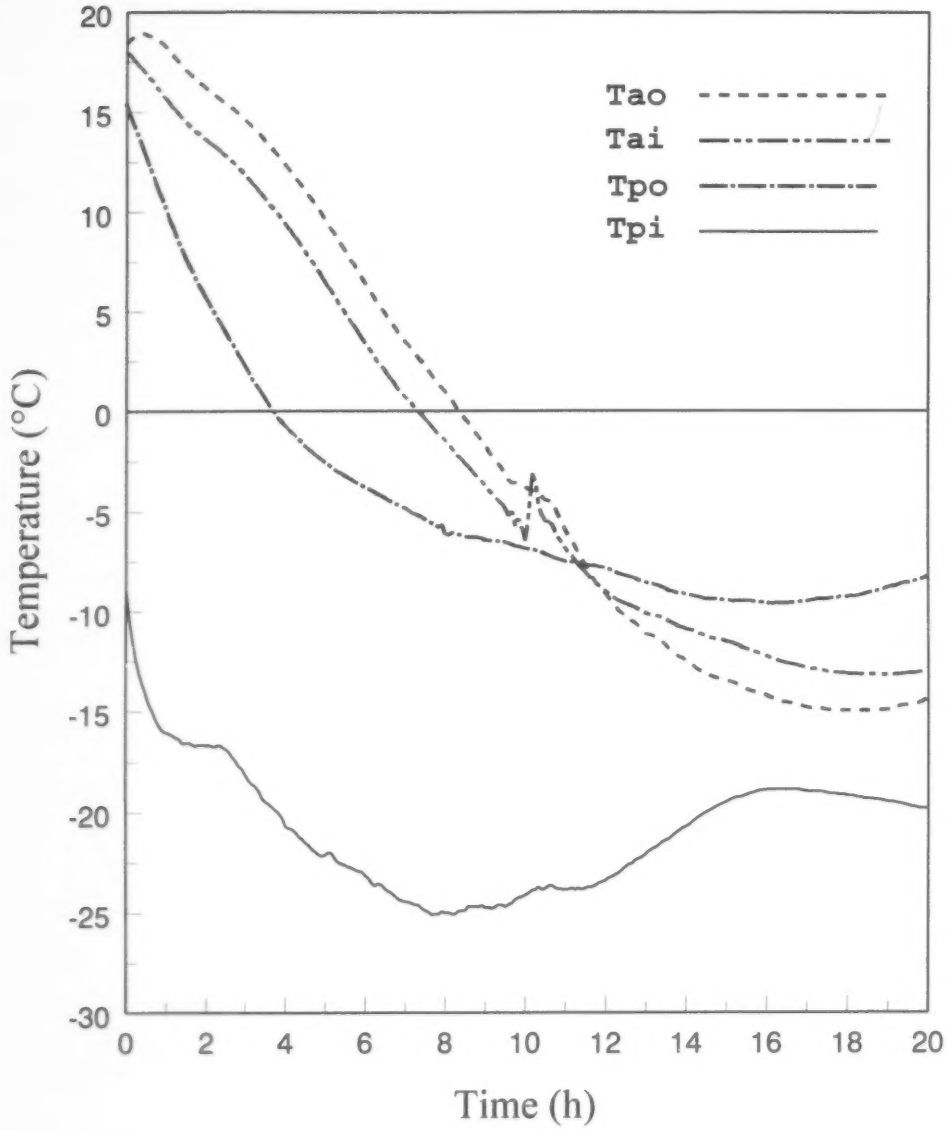

Figure 13. Average temperature-time profiles of propylene glycol chilling fluid at the inlet (T_{pi}) and outlet (T_{po}) of the operative heat exchanger and cabinet air at the inlet (T_{ai}) and outlet (T_{ao}) locations of the chilling cabinet with the system running under the PC1 control program.

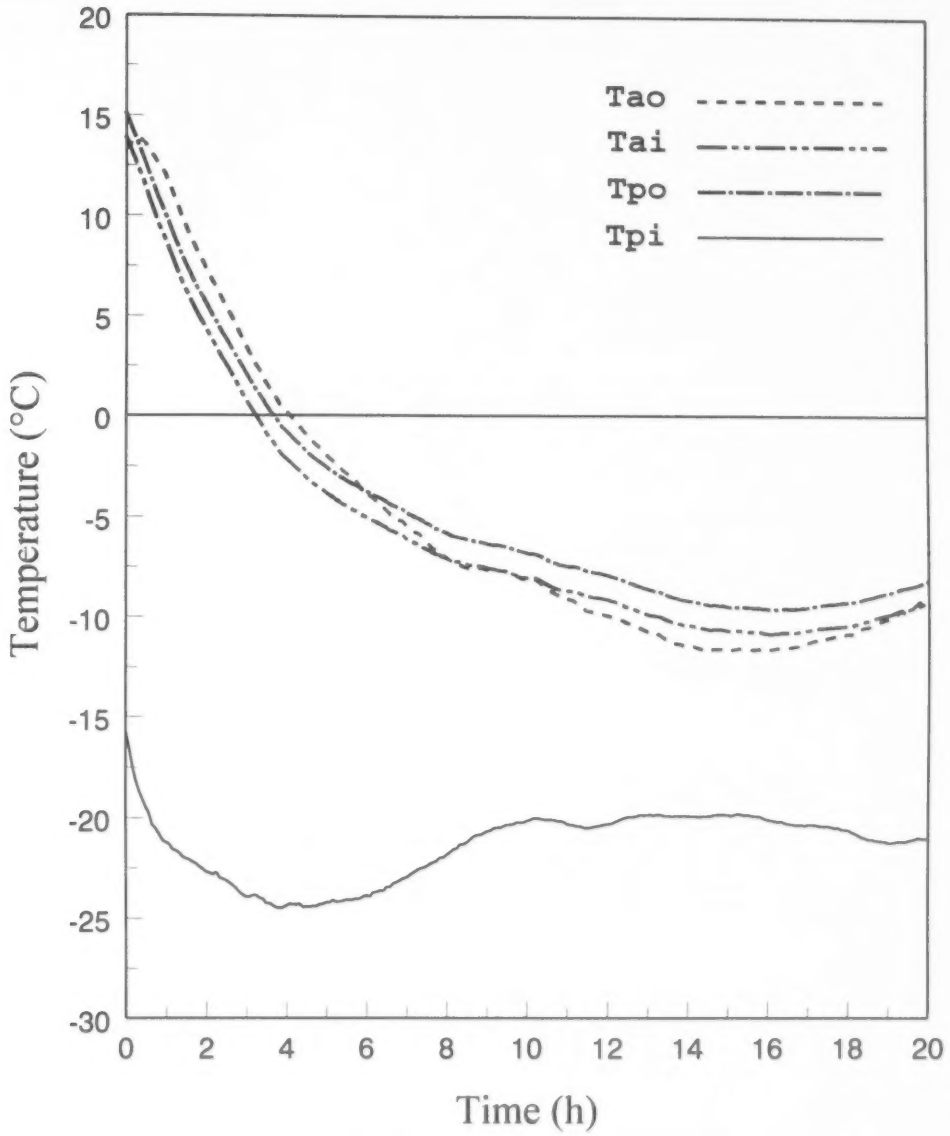

Figure 14. Average temperature-time profiles of propylene glycol chilling fluid at the inlet (T_{pi}) and outlet (T_{po}) of the operative heat exchanger and cabinet air at the inlet (T_{ai}) and outlet (T_{ao}) locations of the chilling cabinet with the system running under the PC2 control program.

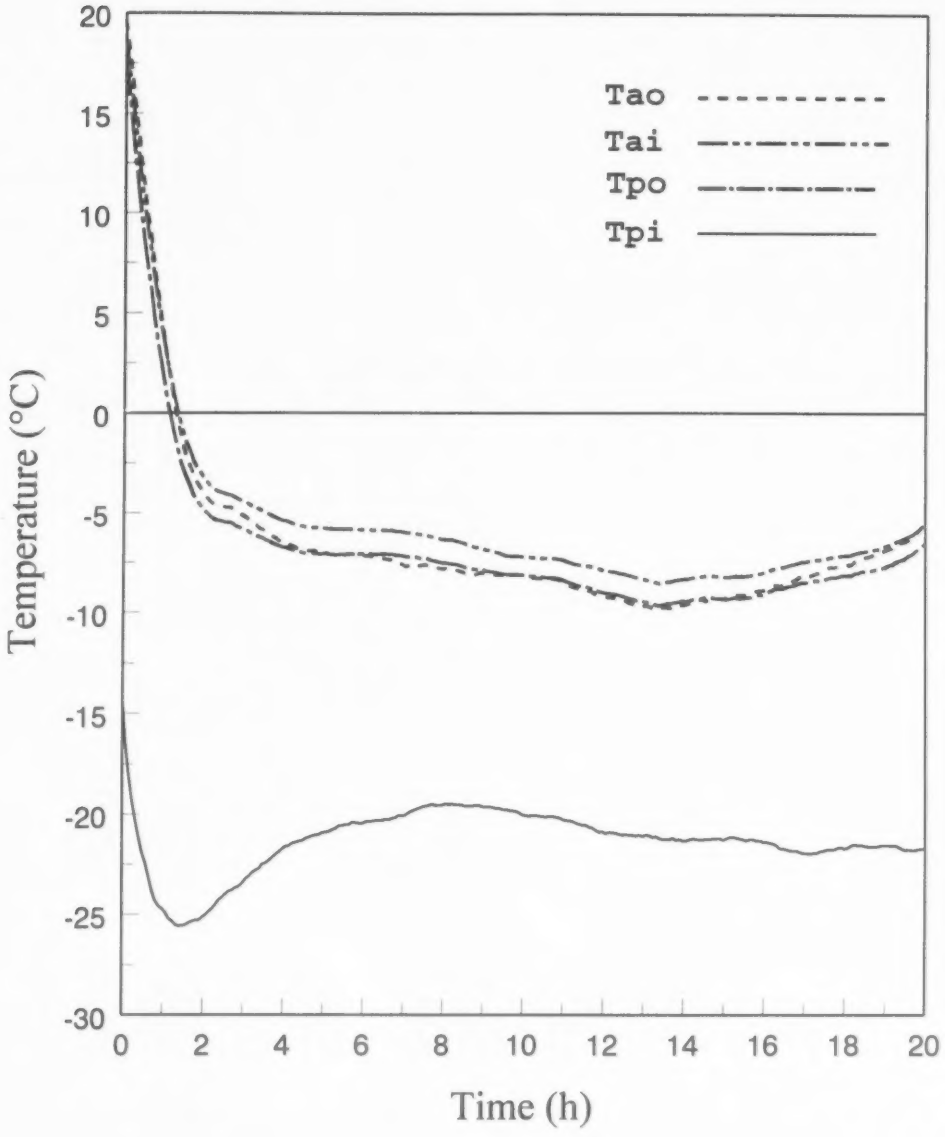

Figure 15. Average temperature-time profiles of propylene glycol chilling fluid at the inlet (T_{pi}) and outlet (T_{po}) of the operative heat exchanger and cabinet air at the inlet (T_{ai}) and outlet (T_{ao}) locations of the chilling cabinet with the system running under the PC3 control program.

(-12.69°C), second lowest for the PC2 process (-10.21°C) and highest for the PC3 process (-8.79°C). These temperatures were reached earliest under the PC3 program and latest under the PC1 program (Fig. 16a).

As expected, beef sides did not attain thermal equilibrium during the observed 22 h of chilling. This was evident from the mean temperature differences between the loin and hip centres after 20 hs, with values of 11.1, 10.0, 7.8, and 7.2°C for the PC1, CON, PC2, and PC3 treatments, respectively. However, air temperature increased during the latter stages of (experimental) chilling, indicating that interior carcass chilling was being accomplished increasingly by thermal equilibration of the carcass muscles, and less by surface heat transfer. Average carcass surface temperatures under the experimental treatments were at sub-zero temperatures for the latter 11-14 h, and were reduced to final (20 h) temperatures of -5.8, -3.7, and -3.2°C for the PC1, PC2, and PC3 treatments, respectively. In contrast, the final average surface temperature of conventionally chilled sides was +3.9°C.

These results are consistent with the fact that the control programs were designed to accomplish different percentages of the total chilling requirement during the early period of chilling (e.g., 0-10 h); that amount increasing in the order PC1-PC2-PC3. This is further reflected in the mean and maximum air temperature decline rates reported in Table 3 for each process during their respective initial phases. In the early phase for each process (i.e., 10, 8, or 2 h) the average maximum air temperature decline rate[11] was

[11] "maximum decline rate" denotes highest absolute value of the negative temperature vs. time slope.

greatest for PC3 and least for PC1. Thus, while the PC1 program established conditions for a relatively constant thermal load (i.e., constant sensible heat flux from the beef side), it also imposed a requirement for a final process air temperature that was 3.9°C and 2.5°C lower than that imposed by the PC3 and PC2 programs, respectively.

For all runs, the PG fluid exhibited its greatest temperature rise between the inlet and outlet locations of the PG/air heat exchanger during the early phase of each process. As the outlet PG temperature declined with the air temperature over time, particularly during the early stages of chilling, this PG temperature difference tended to diminish. Also, this temperature difference declined when the refrigeration system was unable to maintain a low inlet PG temperature (i.e., about -20 °C) during the periods of peak thermal load. To compensate for such reductions in the chilling potential of the PG fluid (i.e., $(T_{po}-T_{pi})$), the control system responded by increasing the PG flowrate. Thus, the peak PG flowrate occurred earliest for the PC3 process (6.58 h) and latest for the PC1 process (17.50 h). The relatively high flowrate in the latter phase of the PC1 program mainly reflects the proportionately higher heat gains from the surrounding environment resulting from the lower cabinet air temperature required in that phase.

Table 3. Thermal performance attributes of chilling regimes based upon the average chiller environments and system responses to program demands.

Performance Attribute	Chilling Program and Phase					
	PC1 Program		PC2 Program		PC3 Program	
	phase 1	phase 2	phase 1	phase 2	phase 1	phase 2
Duration of phase (h)	10	10	8	12	2	18
Percentage of carcass sensible heat removed during phase[1]	65.2	34.8	70.3	29.7	33.4	66.6
Maximum air temperature decline rate (-°C h^{-1})	2.71	2.46	6.30	0.56	19.53	0.37
Mean air temperature decline rate (-°C h^{-1})	2.28	0.88	2.71	0.16	11.75	0.09
Minimum air temperature decline rate (-°C h^{-1})	1.24	0.17	0.64	-0.99	2.52	-0.72
Maximum average air temperature (°C)	17.77	-3.93	15.11	-6.64	17.82	-5.35
Mean average air temperature (°C)	6.77	-10.19	0.74	-8.95	3.93	-7.59
Minimum average air temperature (°C)	-4.90	-12.69	-6.25	-10.21	-4.76	-8.79
Peak average PG mass flowrate (kg min^{-1})	11.33	43.18	12.19	22.34	9.90	20.11
Time of peak average mass flowrate (h)	9.67	17.50	7.92	15.58	1.50	6.58

1. Max. sensible heat removed from side undergoing temperature decline of 33.3°C over 20 h.

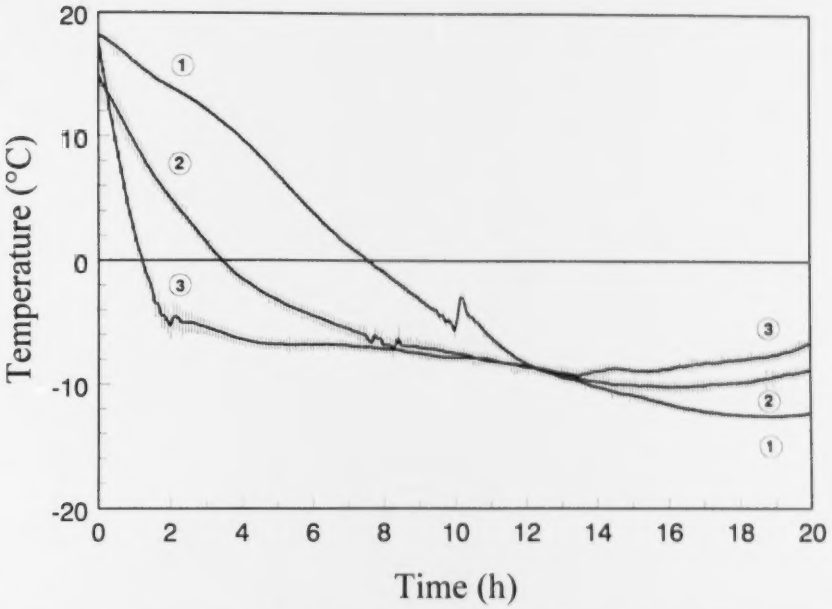

Figure 16a. Average air temperature-time profiles during processes operating under the PC1 (**1**), PC2 (**2**), and PC3 (**3**) control programs. Vertical lines are standard errors.

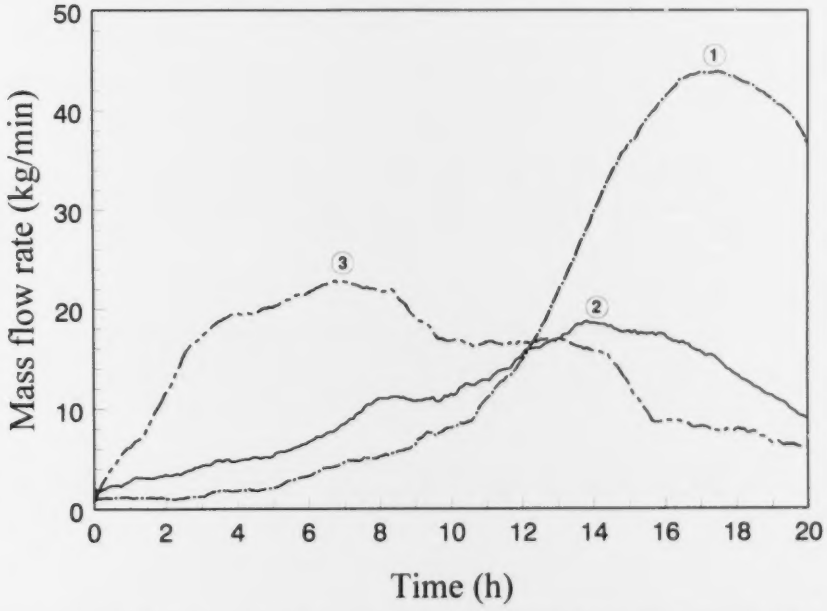

Figure 16b. Average propylene glycol flowrate-time profiles during processes operating under the PC1 (**1**), PC2 (**2**), and PC3 (**3**) control programs.

A brief summary of the observed and important performance characteristics of each process follows.

PC1 Process: The difference between the air and average carcass temperatures remained almost constant during the linear carcass temperature decline phase of the PC1 process. The mean decline rate of the average air temperature profile[12] during this phase ($-2.3^{o}C\ h^{-1}$) was approximately the same as that of the carcass ($-2.2^{o}C\ h^{-1}$). Since a larger percentage of the carcass thermal energy to be removed remained until the latter part of the process (as compared to PC2 and PC3), and since the difference between the PG inlet and outlet temperatures was least towards the end of the process, the PG flowrate peaked during the final four hours of the process.

PC2 Process: For the PC2 process air and PG-outlet temperatures steadily declined when average carcass temperature decline rates were greatest. However, the air temperature declined at a more gradual rate for PC2 as compared to PC3 since the initial chilling load was lower. During the second phase of PC2 chilling (i.e., 8-20 h), when carcass temperature decline rates were lowest, the air temperature declined very slightly at first, then gradually rose towards the end of the process as the carcass and its surroundings approached thermal equilibrium. At no time was the average PG flowrate greater than the average flowrate produced by both the PC1 and PC3 programs (Fig. 16b).

PC3 Process: During the PC3 process, the early exponential rise in the PG mass flowrate reflects the very high chilling demand imposed during the first two hours when

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[12] mean slope of the average air temperature profile over the defined period.

the rate of average air temperature decline was between 2.5 and 19.5°C min^{-1}. As the PG flowrate increased, the PG outlet temperature and chamber air temperature dropped acutely. However, after this first 2 hours, the PG-outlet and air temperatures remained at relatively constant levels, while the PG-inlet temperature increased over the next four to five hours. Maintaining that nearly-constant air temperature (range: -5.4 to -8.8°C), despite the increasing PG-inlet temperature, demanded a continuous increase in the PG flowrate until the PG-inlet temperature stopped rising after about 7 hours. Beginning at this time the PG flowrate slowly declined from a peak value of about 22 kg min^{-1} to a final value of about 5 kg min^{-1}. During this latter 11 hours of the process both air and PG-outlet temperatures gradually converged towards the final average carcass temperature of 0°C, as the carcass and its surroundings approached thermal equilibrium.

Defrost control

The defrost system permitted uninterrupted carcass chilling throughout all of the 36, 20 hour runs, satisfying design expectations. With the lower threshold inlet air velocity set to a value of 3.5 m s^{-1} for all runs, the average number of required defrost events were 0.89 (±0.04)[13], 1.57 (±0.69)[12] and 1.67 (±0.17)[12] for the PC1, PC2 and PC3 processes, respectively.

The defrosting action of the system is best illustrated by the inlet-air velocity profiles of typical process runs operating under the three control programs, as provided in Fig. 17. The timing of each defrost event is indicated by the sudden resumption of

[13] standard error

maximum air flow. It should be noted that the maximum air velocities of each (defrosted) heat exchanger differed by about 0.10 m s^{-1}; which is attributed to the differences between the air duct lengths and bend patterns of the two heat exchanger units. Neglecting minor apparent air velocity fluctuations (i.e., turbulence or anemometer effects or both), the decay in air velocity caused by the accumulation of frost occurred at a constant rate (Fig. 17). However, frosting of the operative heat exchanger was not evident from the velocity profiles until the outlet air temperature dropped below about 0°C (i.e., at approximately 4 h in Figs. 16a and 17).

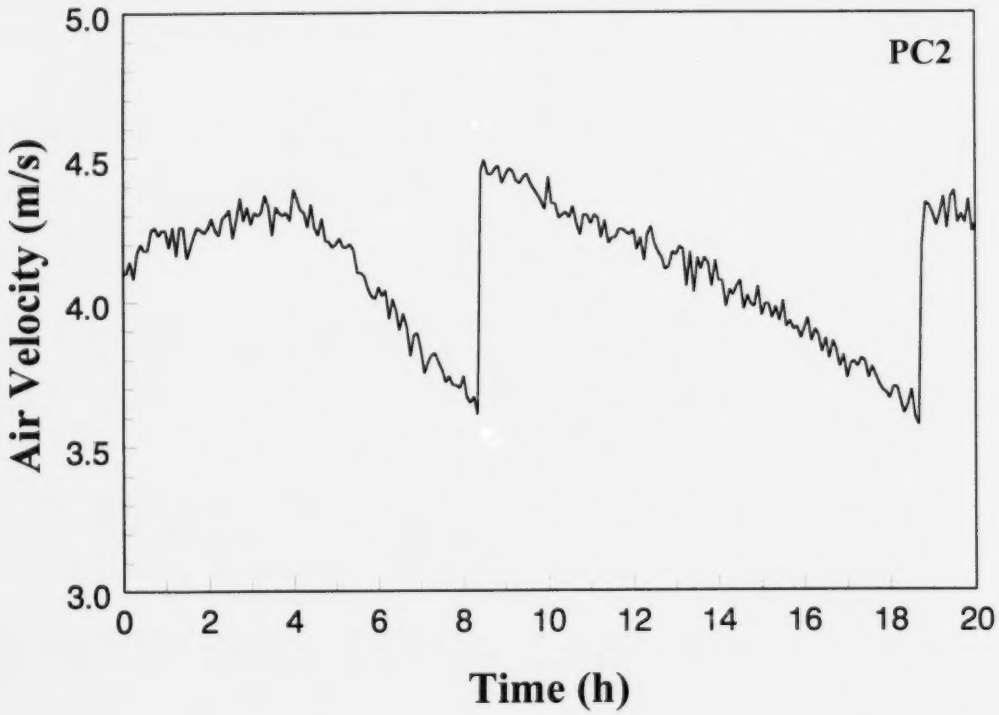

Figure 17. Typical air velocity-time profile during chilling process (result for PC2 program shown).

Pre-chilling the alternate heat exchanger, prior to switching airflow from the frosted unit to that exchanger, appears to have been effective in eliminating or substantially reducing unwanted, sudden changes to the cabinet air temperature, as no such changes were observed. Moreover, there were no detectable negative effects of defrost actions on the average beef side temperature, indicating that the PLC control program responded effectively to the abrupt increase in air velocity preceding each defrost event.

Precision of average carcass temperature control

The chilling system was capable of keeping the absolute difference between the target and observed average carcass temperature for the PC1, PC2, and PC3 processes to average values of 0.07 (±0.03), 0.06 (±0.03) and 0.11 (±0.04)°C, respectively. This ability is graphically illustrated in Fig. 18 in which the mean temperature deviation and its standard error are plotted over the first 10 hour period for each of the three processes. In contrast to these results, the resolution of each RTD temperature reading was ±0.25°C (note: because average side temperatures were based on five measurements, the probability of an average value being maximally high or low, +0.25°C or -0.25°C, was $^{1}/_{243}$). Thus, the observed temperature control capability, exceeded the measurement resolution of the RTDs that were used.

As displayed in Fig. 18, the absolute average control error tended to increase or drift with time, particularly during the PC1 and PC2 processes. This drift was very slight however, such that the average carcass temperature control error was less than any of the

mean standard errors of the experimental variations in muscle temperatures. Since variation in the control drift was also relatively small, variation in temperature responses of sides due to control error was almost certainly negligible in comparison to that which was due to random or uncontrolled sources of variation. The variation between runs in muscle temperature is reflected in the mean standard error values for each process and muscle location, which is discussed below.

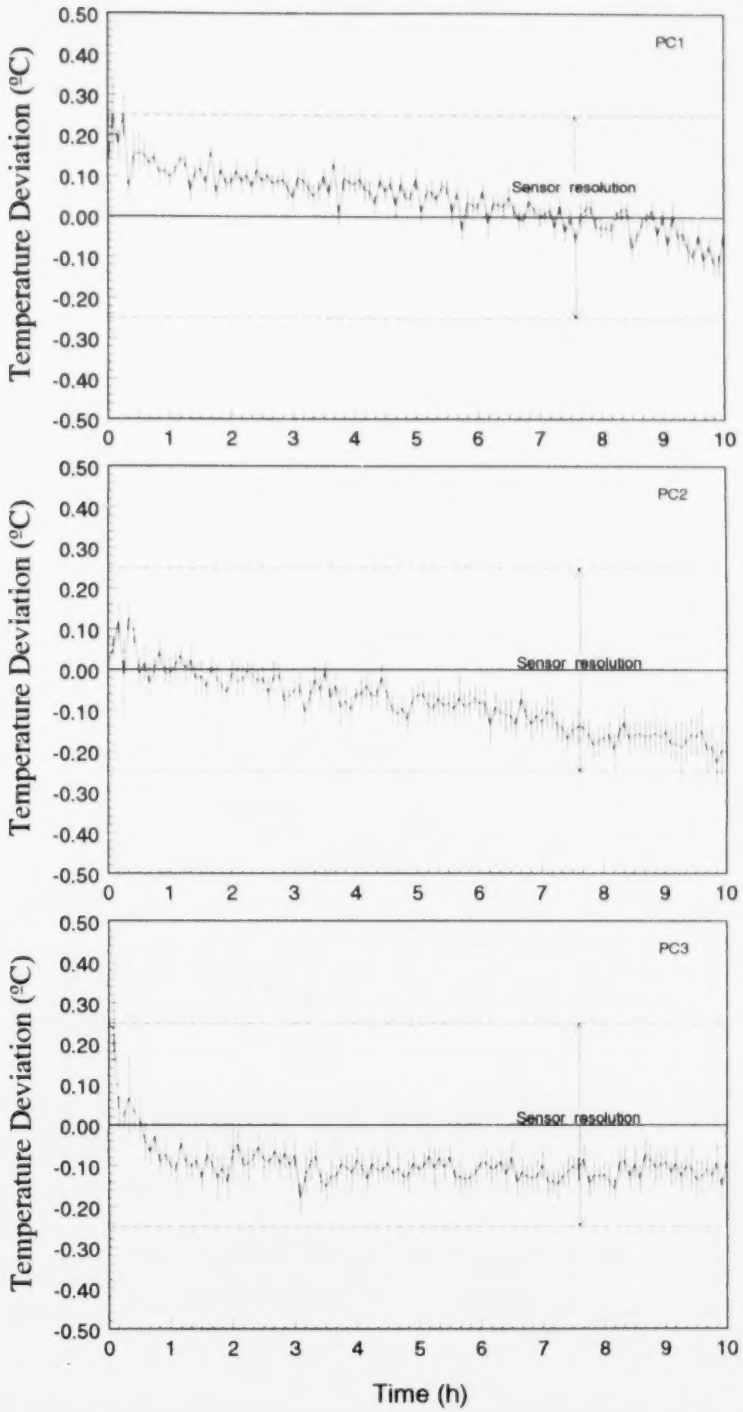

Figure 18. Average deviation between target and measured average carcass temperatures during programmed chilling. Vertical lines are standard errors.

Effect of treatment on chilling time for specific muscle locations

In Fig. 19 are shown temperature-time profiles of the average carcass surface[14] and cabinet air[15], and those of the deep (or "centre"), hip, loin, and neck locations for each of the three, 20-h chilling processes. These temperature histories, as expected, were clearly dependent upon the chilling treatment program. For example, the time required for muscle temperatures to reach the critical or threshold temperatures of 10 and 0°C varied according to treatment and, in some cases, beef side orientation in the chiller (i.e., left vs right). These times were determined for each run, and the results are presented in Tables 4 and 5. The time required for the muscle temperature to fall to 10°C (θ_{10}) was, for all muscle locations, lowest for the PC3 treatment, whereas the greatest such time was achieved with either the conventional or PC1 process. The reported differences in θ_{10} amongst chilling treatments were all significantly different ($p<0.01$), whereas side (orientation) did not universally exert an effect on either θ_{10} or θ_0. Significant differences ($p<0.05$) in θ_{10} of the loin centre location between left and right sides were found for the PC1, PC2 and PC3 treatments, and in θ_0 between left and right sides of the loin and hip surface locations for the control treatment. Similarly, significant differences ($p<0.05$) in θ_0 of the loin surface location between left and right sides were found for the PC2 and PC3 treatments.

The expected influence of muscle depth on the chilling times θ_{10} and θ_0 is indicated by the times reported in Tables 4 and 5, respectively, for the different tissue

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[14] based upon mean of hip and loin surface temperatures.

[15] based upon mean of chilling cabinet air temperatures at air inlet and outlet locations.

depths of the loin and hip. Moreover, the differences in θ_{10} and θ_0 chilling times between centre and deep locations of the loin and hip locations are a measure of the temperature gradient within the loin and hip regions during the periods defined by those time differences (since all temperatures between these extreme locations are intermediate between their values).

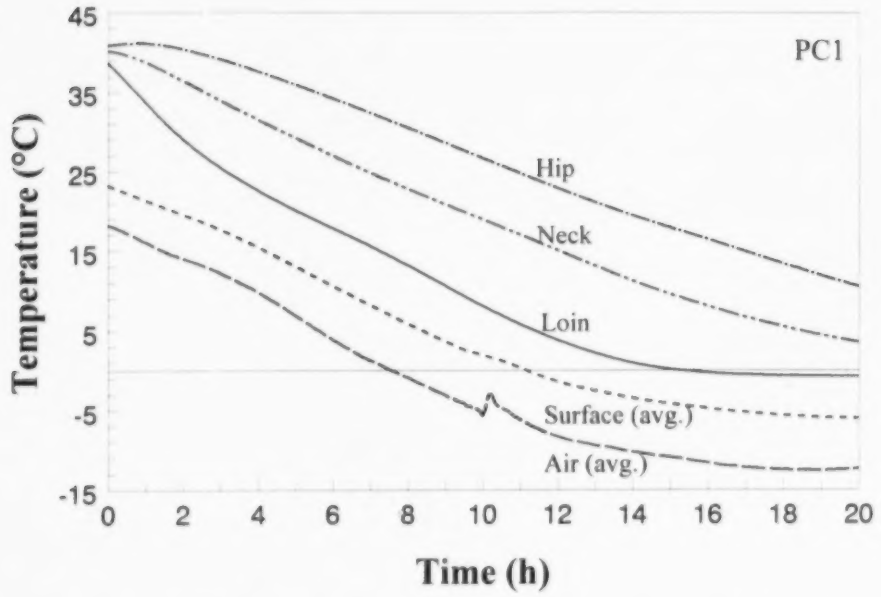

Figure 19a. Average temperature-time profiles of beef side muscle locations and chilling cabinet air during PC1 processing.

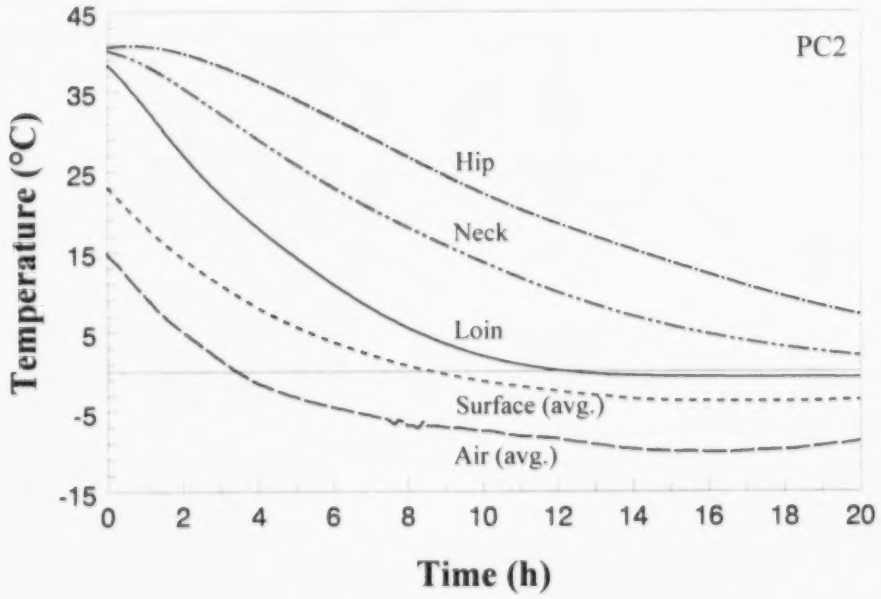

Figure 19b. Average temperature-time profiles of beef side muscle locations and chilling cabinet air during PC2 processing.

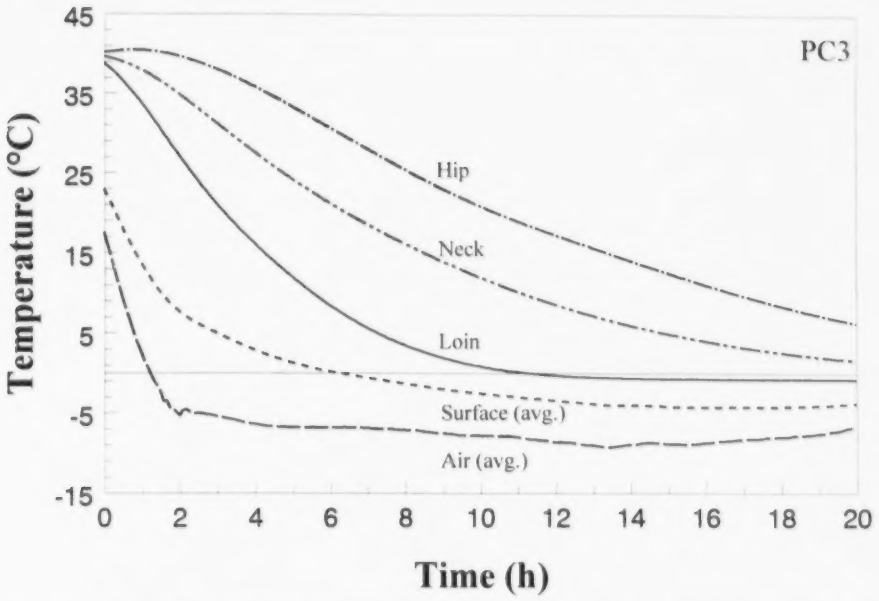

Figure 19c. Average temperature-time profiles of beef side muscle locations and chilling cabinet air during **PC3** processing.

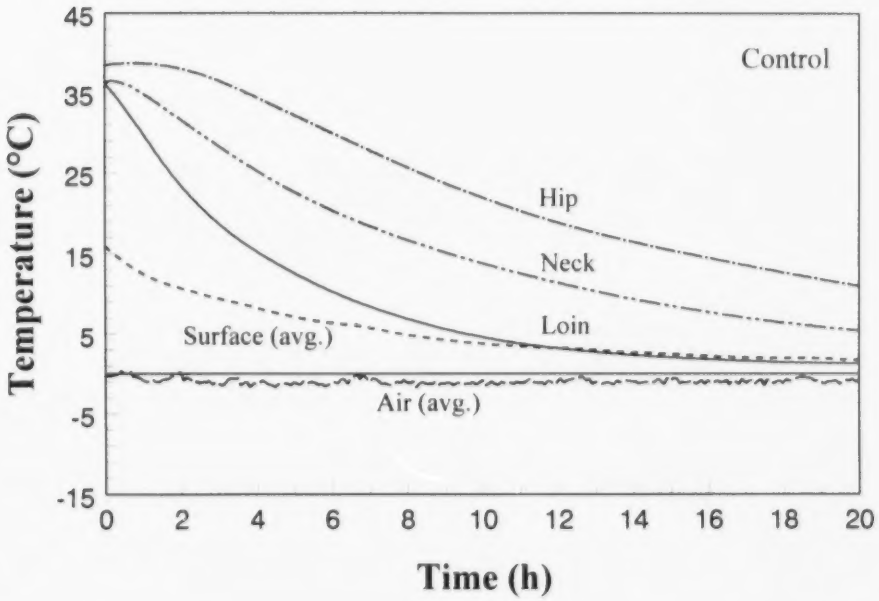

Figure 19d. Average temperature-time profiles of beef side muscle locations and chilling cabinet air during conventional (CON) processing.

Table 4. Time (θ_{10}; h) for muscle temperatures of left and right sides to decline to 10°C from initiation of chilling.‡

Control Program	Hip Centre		Hip Mid-depth		Hip Surface		Loin Centre		Loin Surface		Neck Centre	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
PC1	17.01 **a** (0.28)	16.81 **a** (0.28)	14.76 **a** (0.43)	13.67 **a** (0.43)	6.08 **a** (0.37)	6.64 **a** (0.37)	9.47 ***a** (0.19)	8.98 ***a** (0.19)	6.25 **a** (0.32)	6.94 **a** (0.32)	14.39 **a** (0.40)	15.35 **a** (0.40)
PC2	14.13 **b** (0.31)	14.08 **b** (0.31)	12.43 **b** (0.47)	11.38 **b** (0.47)	2.92 **b** (0.41)	3.43 **b** (0.41)	6.89 ***b** (0.21)	5.85 ***b** (0.21)	3.11 **b** (0.35)	4.02 **b** (0.35)	12.16 **b** (0.44)	11.56 **b** (0.44)
PC3	13.24 **c** (0.28)	13.61 **c** (0.28)	10.81 ***c** (0.43)	9.24 ***c** (0.43)	1.29 **c** (0.37)	1.23 **c** (0.37)	5.67 ***c** (0.19)	5.39 ***c** (0.19)	1.70 **c** (0.32)	2.26 **c** (0.32)	10.86 **c** (0.40)	11.33 **b** (0.40)
CON	20.67 **d** (0.28)	20.72 **d** (0.28)	14.13 **a** (0.43)	14.02 **a** (0.43)	2.20 ***b** (0.37)	3.45 ***b** (0.37)	5.94 **d** (0.19)	6.37 **b** (0.19)	1.43 ***c** (0.32)	2.99 ***c** (0.32)	13.72 **d** (0.40)	12.92 **d** (0.40)

‡ Numbers in brackets are standard errors based upon between-treatment comparisons.

a-d Results bearing different letters differ significantly within muscle location groups of same side ($p<0.01$).

* Results for left and right sides within muscle location group sharing same treatment differ significantly ($p<0.05$).

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Table 5. Time (θ_0) for muscle temperatures of left and right sides to decline to 0°C from initiation of chilling‡.

Control Program	Hip Mid-depth		Hip Surface		Loin Centre		Loin Surface		Neck Centre	
	Left (h)	Right (h)	Left (h)	Right (h)	Left (h)	Right (h)	Left (h)	Right (h)	Left (h)	Right (h)
PC1	24.80 † (--)	26.17 † (--)	11.26 **a** (0.51)	11.81 **a** (0.51)	15.14 **a** (0.36)	14.90 **a** (0.36)	10.72 **a** (0.41)	11.66 **a** (0.41)	24.09 † (--)	26.09 † (--)
PC2	27.94 † (--)	24.90 † (--)	8.17 **b** (0.57)	9.67 **b** (0.57)	12.23 **b** (0.40)	11.58 **b** (0.40)	7.19 ***b** (0.45)	8.67 ***b** (0.45)	26.33 † (--)	24.32 † (--)
PC3	26.89 † (--)	23.55 † (--)	6.37 **c** (0.51)	5.41 **c** (0.51)	11.18 **c** (0.36)	10.86 **c** (0.36)	5.43 ***c** (0.41)	6.73 ***c** (0.41)	24.08 † (--)	24.35 † (--)
CON	34.21 † (--)	35.58 † (--)	31.65 † (--)	31.20 † (--)	37.90 † (--)	40.11 † (--)	31.79 † (--)	31.82 † (--)	31.72 † (--)	35.76 † (--)

‡ Numbers in brackets are standard errors based upon between-treatment comparisons.

a-d Results bearing different letters differ significantly within muscle location groups of same side ($p<0.01$).

† Results without standard error values were extrapolated from the average temperature-versus-time profile.

* Results for left and right sides within muscle location group sharing same treatment differ significantly ($p<0.05$).

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For the loin, the mean differences in θ_{10} between the deep and surface locations (time-spread) were 3.54, 2.90, and 2.63 h for the PC3, PC2, and PC1 processes, respectively. The time-spread results for the PC1 and PC3 processes were significantly different, as were the results for PC2 and PC3 ($p<0.01$). For the hip region, these mean time-spread differences were 12.17 for PC3, 10.86 for PC2, and 10.55 h for PC1. Again, the time-spread results for the PC1 and PC3 processes were significantly different, as were the results for PC2 and PC3 ($p<0.01$). The loin and hip θ_{10} time-spread results for the PC1 and PC2 processes were not significantly different ($p>0.05$).

A similar but weaker trend for the θ_0 time-spread (i.e., deep θ_0 - surface θ_0) values associated with the loin were obtained. For the loin, the mean θ_0 time-spread differences were 4.94, 3.94, and 3.83 h for PC3, PC2, and PC1, respectively. These time-spread results for the PC1 and PC3 processes were significantly different ($p<0.03$), as were the results for PC2 and PC3 ($p<0.06$). For the hip, the θ_0 time-spread differences were not directly estimable since the hip centre (deep hip) temperature did not decline to or below 0°C in 22 h. The loin θ_0 time-spread results for the PC1 and PC2 processes were not significantly different ($p>0.05$).

Thus, for the loin, the PC1 and PC2 processes resulted in more spatially uniform temperatures than those provided by the PC3 process. For the hip, the PC1 and PC2 processes also resulted in more uniform temperatures than those provided by the PC3 process, at least until the deep hip temperature had declined to 10 °C.

The times (θ_0) for the loin surface and centre temperatures to decline to 0°C exhibited a similar pattern in that θ_0 was least for PC3 and increasingly greater for the PC2, PC1, and conventional chilling treatments, in that order (Table 5). The processing treatment choice had a significant effect on θ_0 for the loin muscle locations at all treatment levels. Carcass orientation did not produce a measurable effect on θ_0. Similar results were recorded for the hip surface.

For the deep hip, mid-hip, and neck centre temperatures θ_0 exceeded 22 h, so that for these muscle locations it was only possible to mathematically estimate their θ_0 values by extrapolation. The times for the mid-hip temperatures to decline to 0°C were estimated to be in the 24-28 h range (Table 5). The θ_0 times for every muscle location in sides processed by the conventional chilling method were in the range of 31-36 h.

Variation in muscle temperature profiles

Variations in the transient temperature-time profiles of individual muscles locations were determined. The average temperature-time profiles of each muscle location and for each chill program and side orientation are presented in Figs. 20, 21, 22, 23, 24 and 25. The calculated standard errors associated with each muscle temperature-treatment combination are shown as vertical lines in these figures. The mean standard error values for each such combination are presented in Table 6. The mean standard errors for individual muscle temperatures, which ranged from 0.11 to 1.01°C, were approximately an order of magnitude greater than the mean absolute control error values for each program (i.e., PC1: 0.027; PC2: 0.031; PC3: 0.105°C).

Some of the observed temperature profile variation, for certain defined periods during chilling was found to be attributable to the left versus right configuration of the hanging beef side (i.e., anantiomorphism; the left and right sides of the dressed carcasses used the same support location). The effects of side orientation on individual muscle temperature histories are graphically illustrated in Figs. 26, 27 and 28. These figures show the differences between the mean left and right side temperatures of the six muscle locations, each plotted against chilling time. These differences, which were no more than 2.7 °C, were estimated to be significant ($p<0.05$) during some (but not all) periods of the chilling processes. Generally, these differences were not significant in consideration of variation from uncontrolled factors. Also, with the exception of the experimental control sides, there was a general tendency for these differences to diminish or become smaller as chilling progressed.

Table 6. Mean standard error values for muscle temperatures monitored over 20 hours.

	Mean Standard Error (°C)											
	Hip centre		Hip mid-depth		Hip surface		Loin centre		Loin surface		Neck	
Program ↓	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
PC1	0.19	0.69	0.62	0.71	0.53	0.66	0.49	0.34	0.67	0.65	0.39	0.11
PC2	0.71	0.37	0.34	0.41	0.66	1.01	0.66	0.45	0.67	0.75	0.74	0.94
PC3	0.43	0.42	0.55	0.74	0.49	0.78	0.19	0.26	0.42	0.75	0.48	0.80
CON	0.27	0.46	0.54	0.67	0.42	0.46	0.36	0.39	0.47	0.40	0.48	0.53

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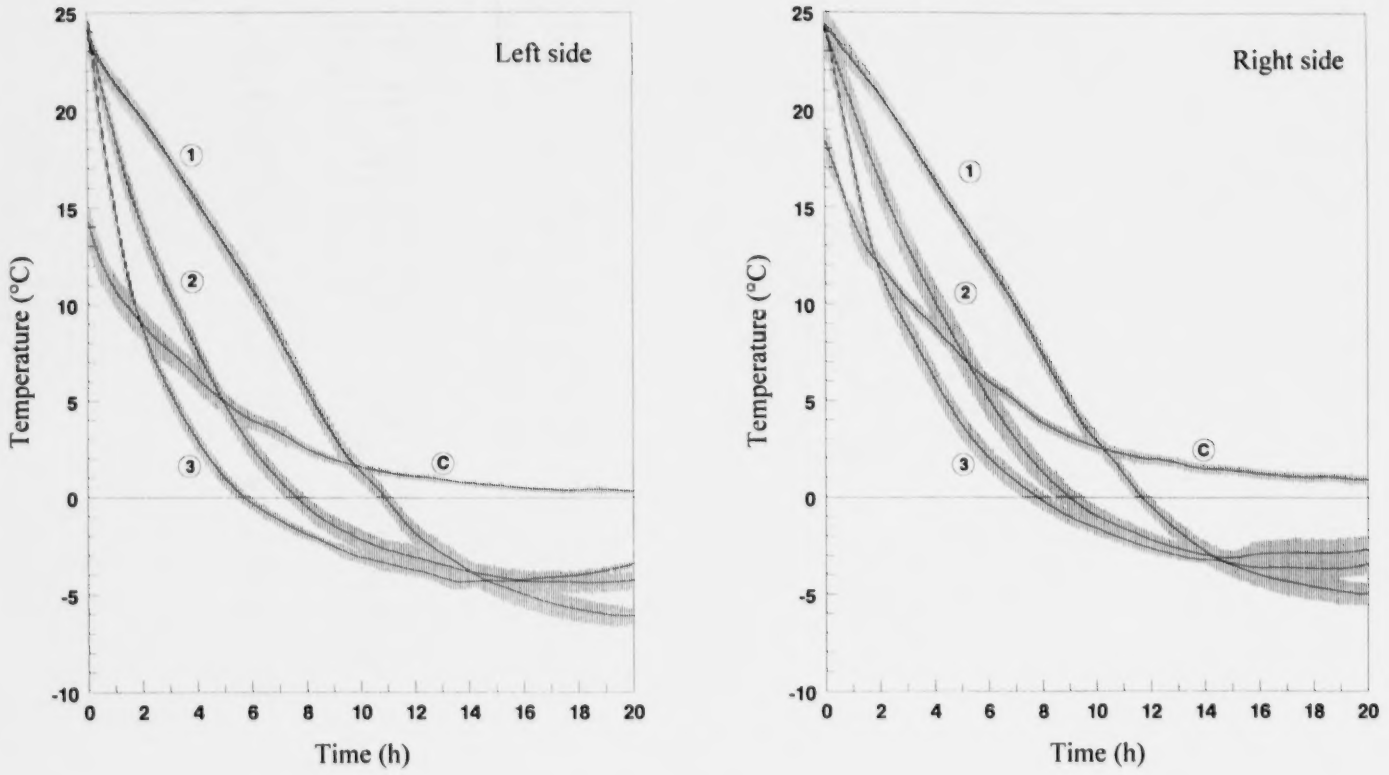

Figure 20. Average temperature-time profiles of the loin surface for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left and right sides. Vertical lines are the standard errors.

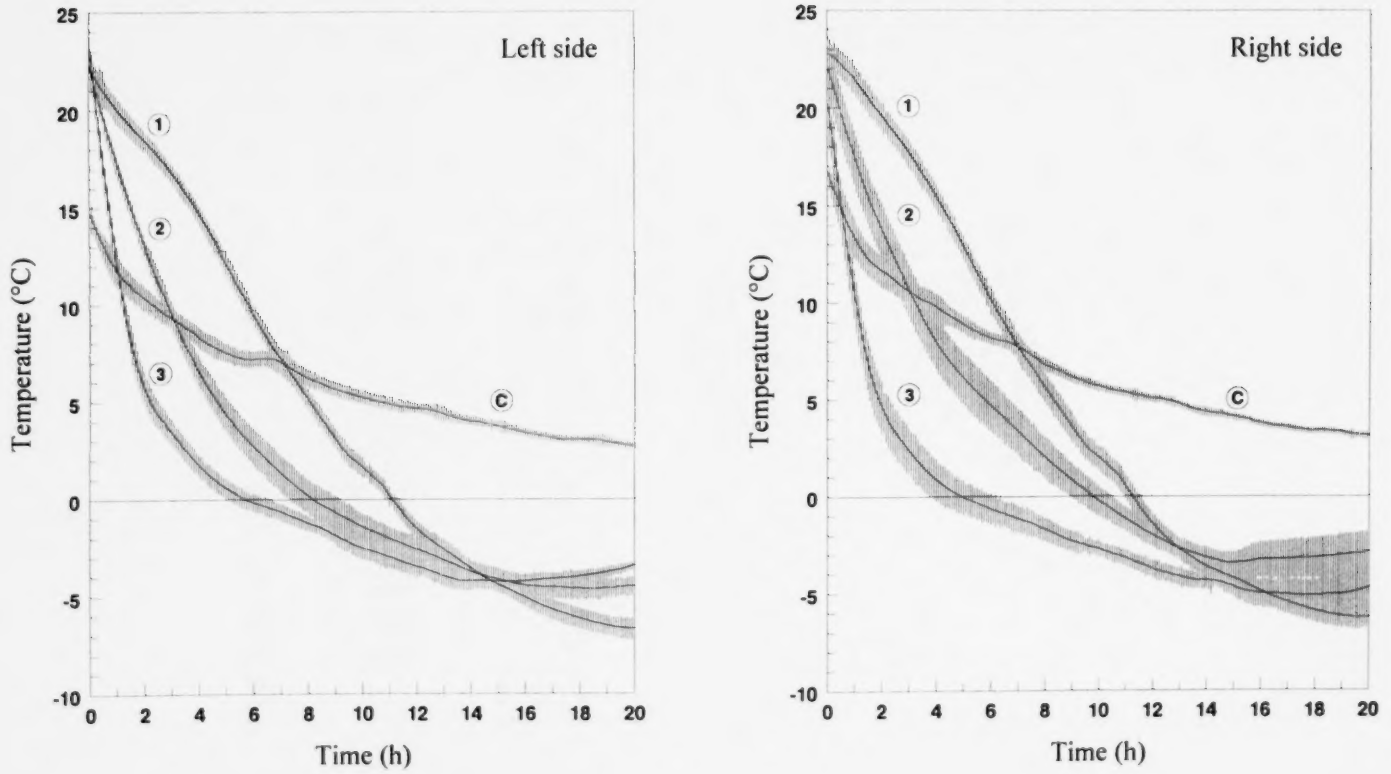

Figure 21. Average temperature-time profiles of the hip surface for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left and right sides. Vertical lines are the standard errors.

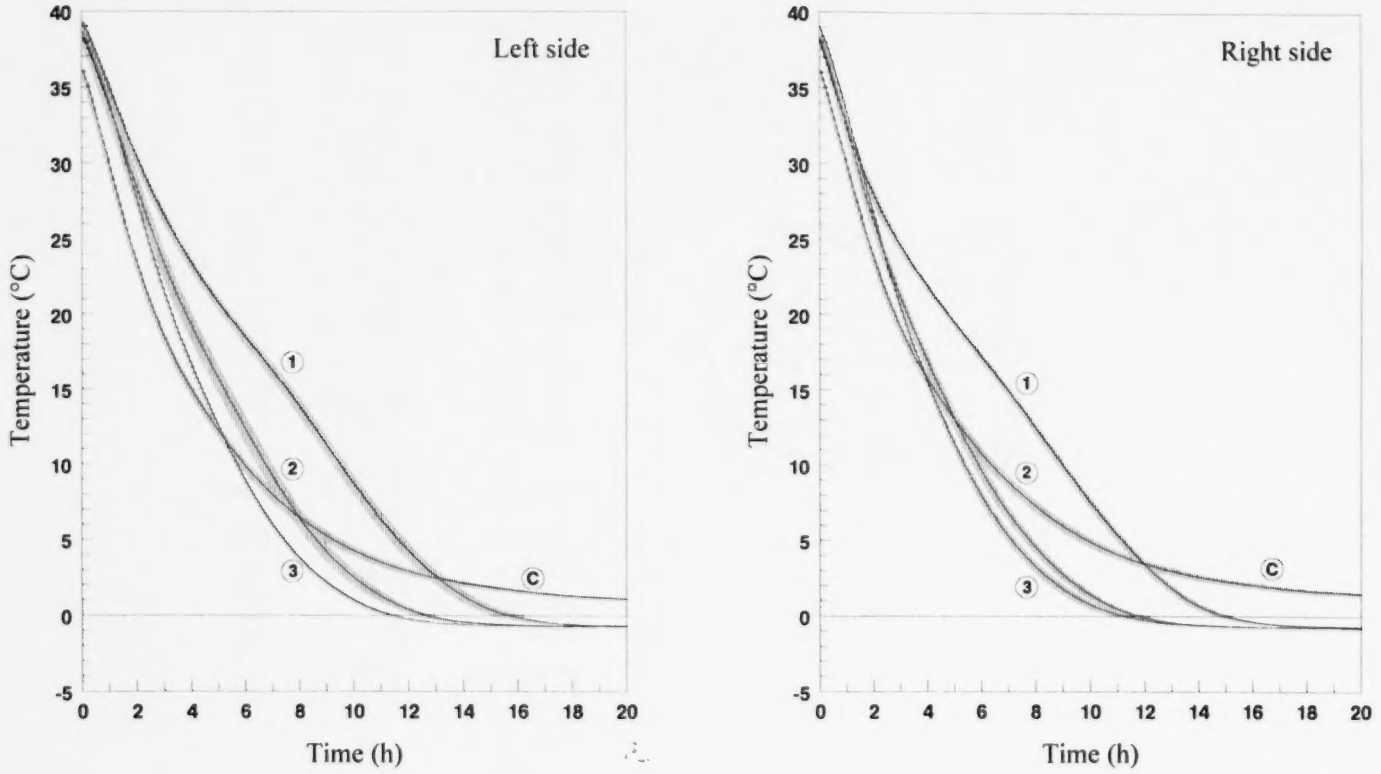

Figure 22. Average temperature-time profiles of the loin centre for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left side and right side. Vertical lines are the standard errors.

001

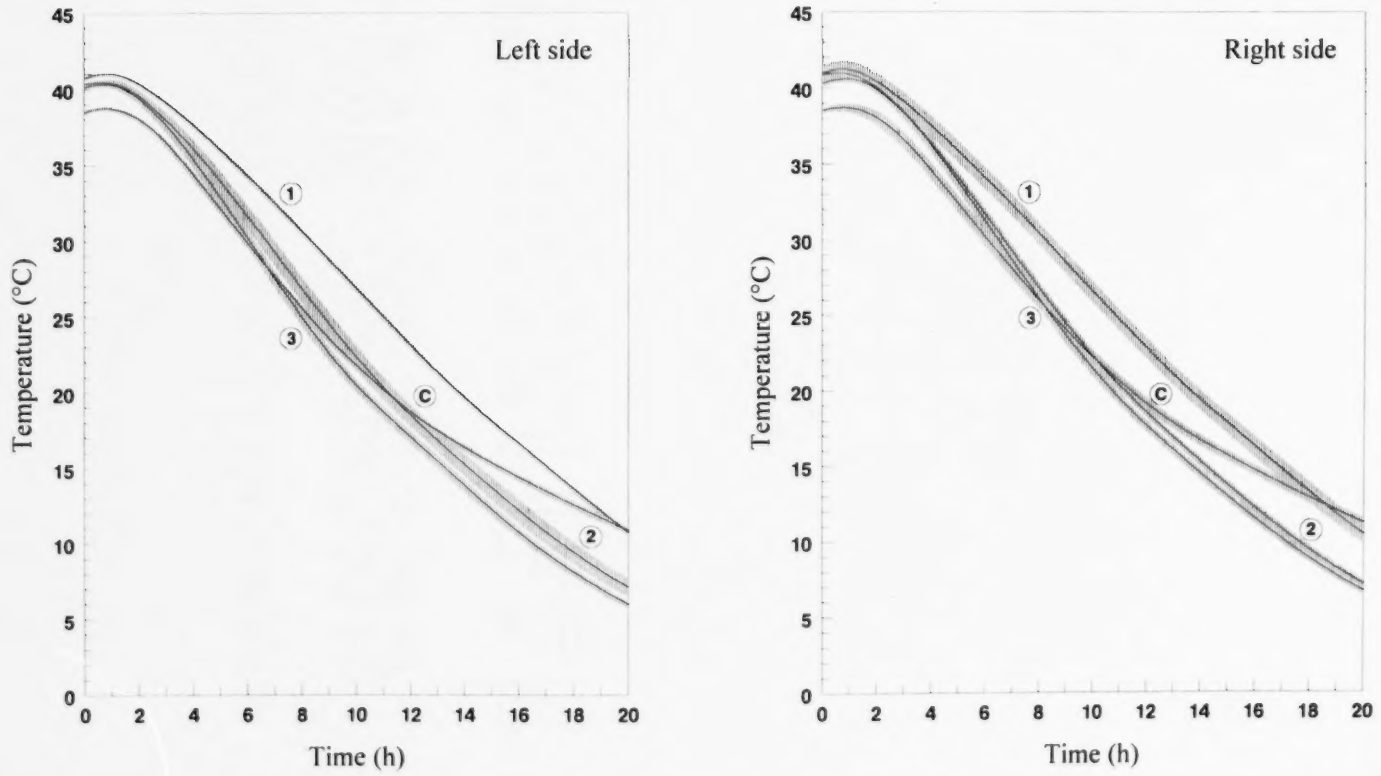

Figure 23. Average temperature-time profiles of the hip centre for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left and right sides. Vertical lines are the standard errors.

101

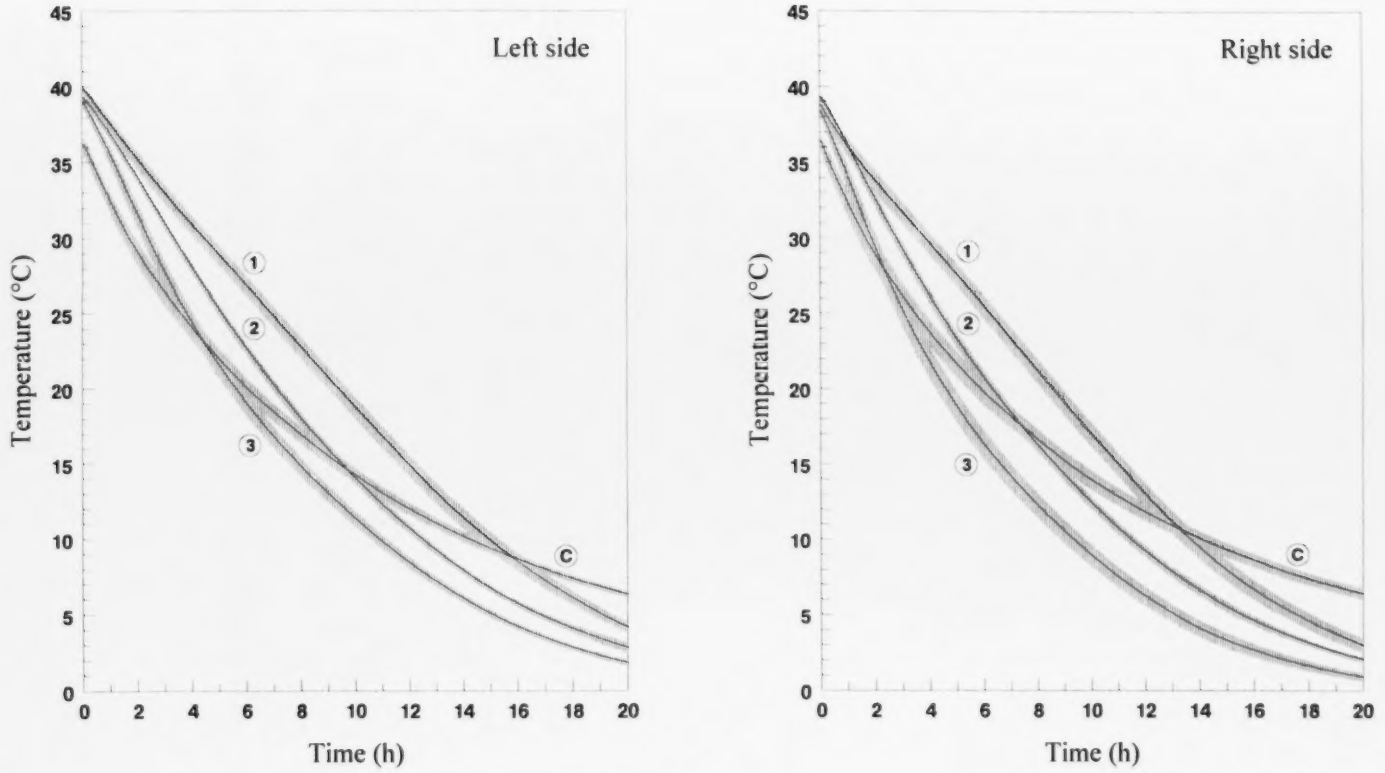

Figure 24. Average temperature-time profiles of the hip mid-depth location for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left and right sides. Vertical lines are the standard errors.

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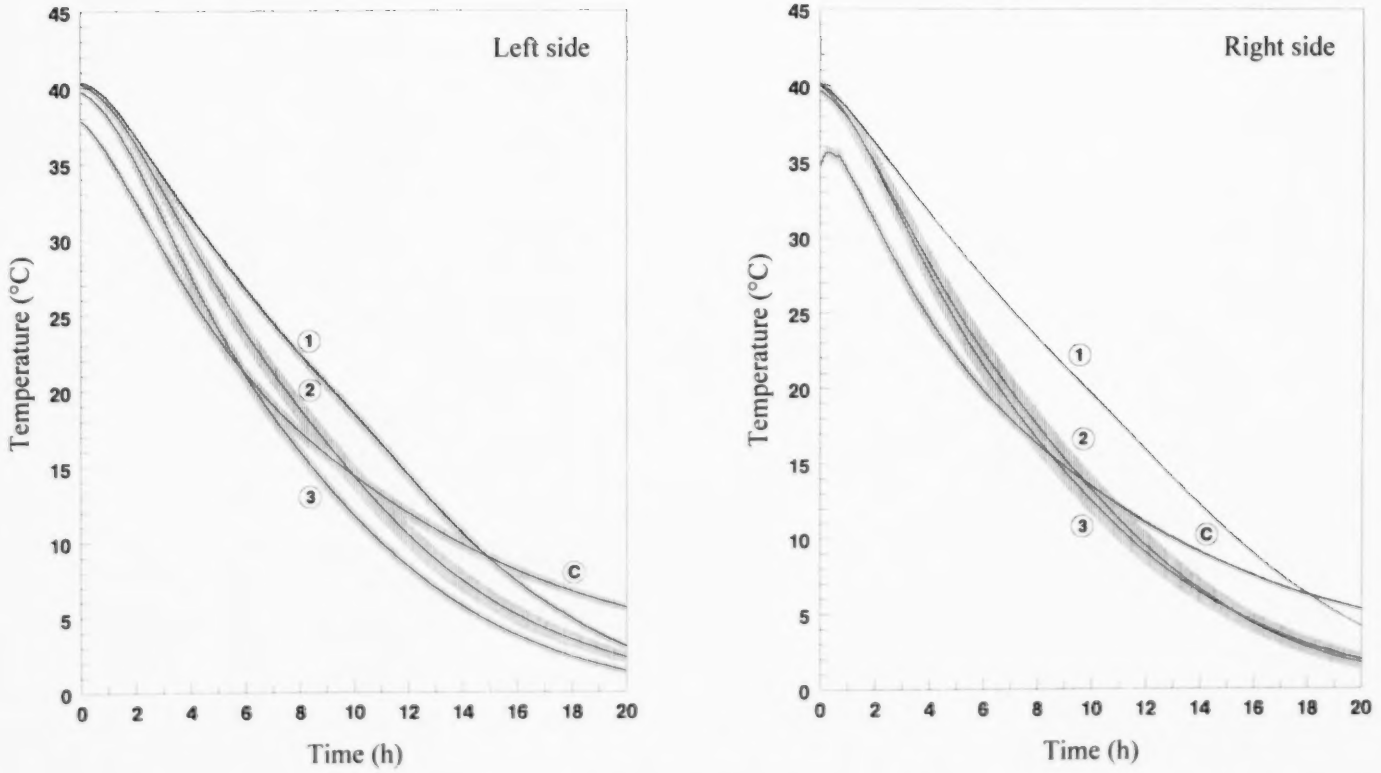

Figure 25. Average temperature-time profiles of the neck centre for the PC1 (**1**), PC2 (**2**), PC3 (**3**) and Control (**C**) processes and for the left and right sides. Vertical lines are the standard errors.

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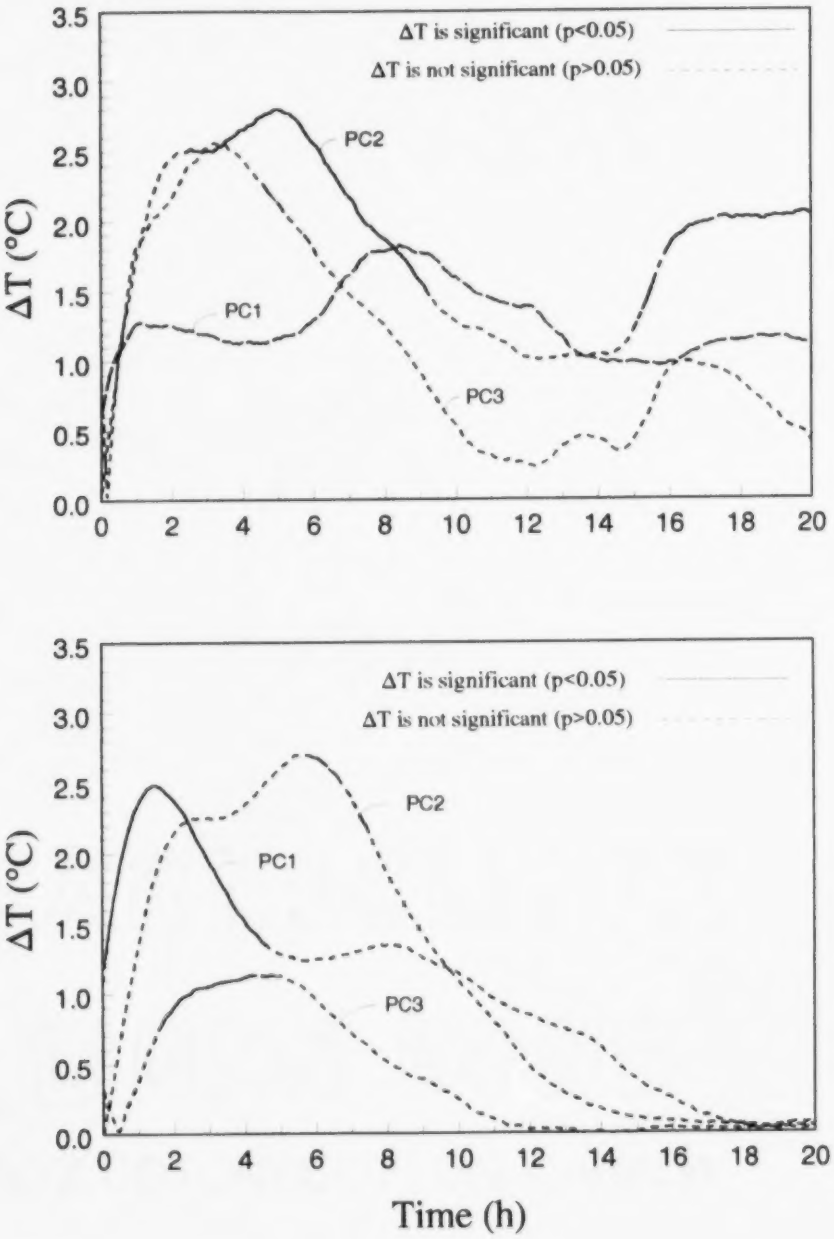

Figure 26. Average difference between left and right side temperatures of the loin surface (top plots) and loin centre (bottom plots) during PC1, PC2, and PC3 processing.

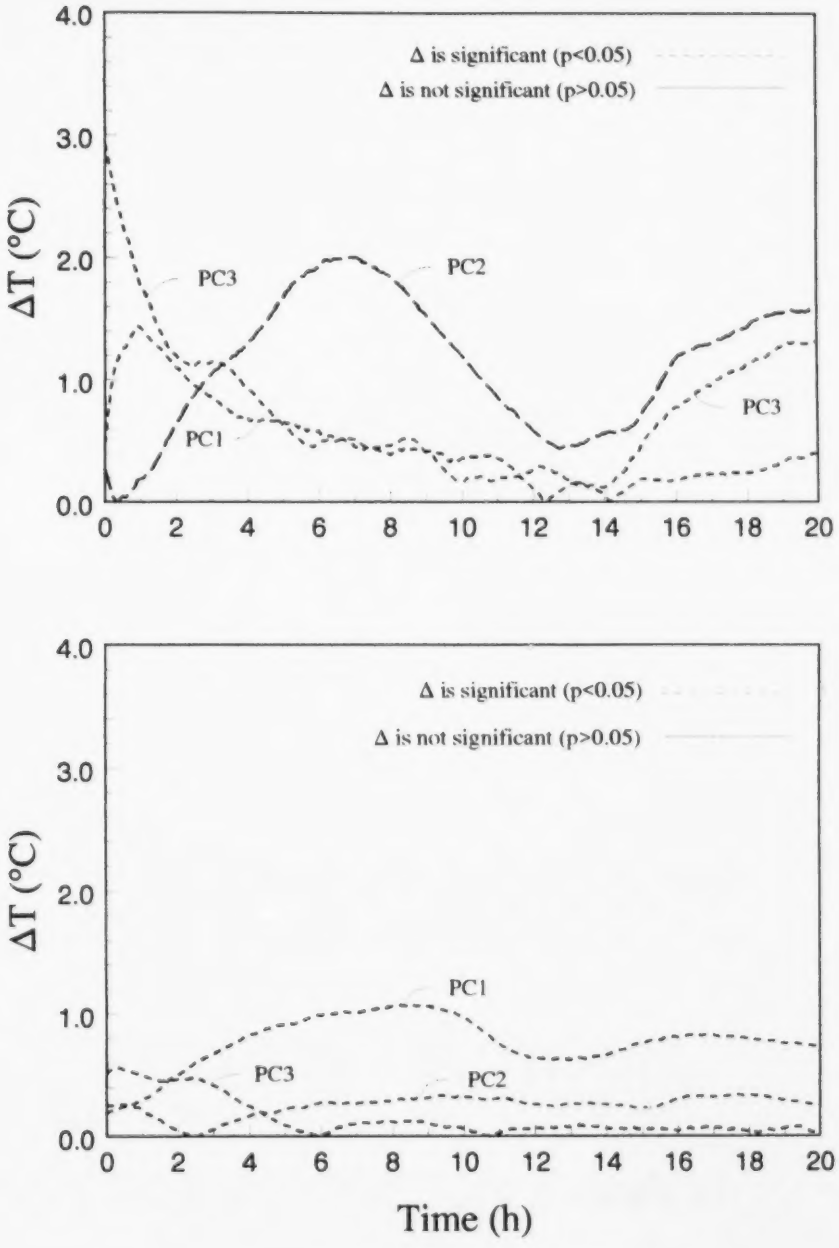

Figure 27. Average difference between left and right side temperatures of the hip surface (top plots) and hip centre (bottom plots) locations during PC1, PC2, and PC3 processing.

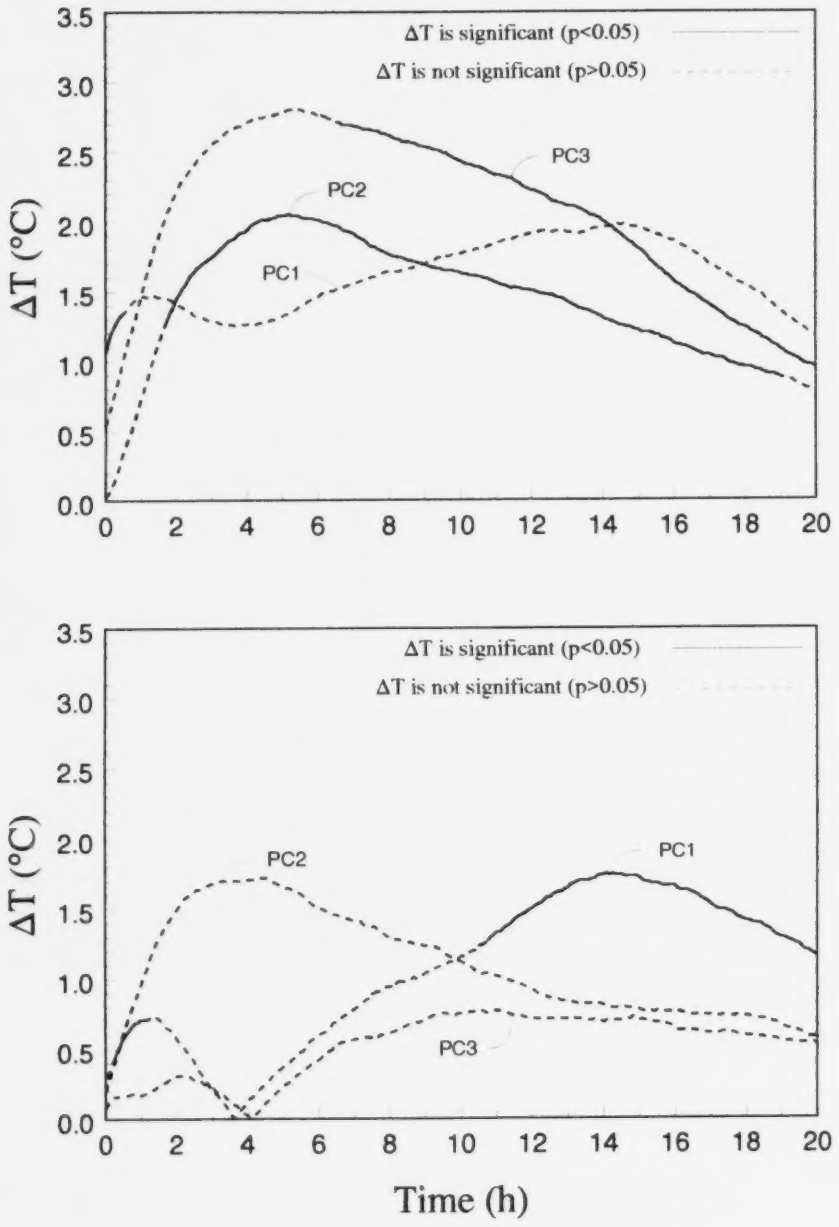

Figure 28. Average difference between left and right side temperatures of the hip mid-depth location (top plots) and neck centre (bottom plots) during PC1, PC2, and PC3 processing.

Effect of initial muscle temperatures on chilling times and temperature variation

The initial uncontrolled temperature of each muscle location (e.g., Tlc(0)) also accounted for some of the muscle temperature history variation, as reflected in the observed relationships between their initial temperatures and their θ_{10} and θ_0 chilling times. Graphical illustrations of the chilling time dependence on initial temperature are provided in Figs. 29, 30, and 31 for the surface locations of the loin undergoing PC1, PC2, and PC3 chilling treatments, respectively. The relationship between initial temperature and chilling time was assumed to follow the linear form:

$$\theta_T = \gamma \cdot (T_i - T_f) \tag{13}$$

The experimental values of γ for the six muscle locations are given in Tables 7 and 8 for θ_0 and θ_{10}, respectively. The sensitivity of chilling time, as reflected in the values of γ, to the initial muscle location temperature varied amongst locations and chilling treatments. Moreover, for the three experimental processes the sensitivity to the initial temperature was found to be inversely related to the initial rate of carcass temperature decline. That is, for all muscle locations and for the final accomplished temperatures of 0 and 10 °C, γ decreased as the rate of initial temperature decline increased. Thus, the experimentally estimated values of γ were least for PC3, greater for PC2, and greatest for the PC1 process. Also, "rapid initial chilling" reduced variability in times for individual muscles to fall to specified above-zero temperatures. However, as presented above, "rapid initial chilling" also reduced carcass temperature uniformity during chilling.

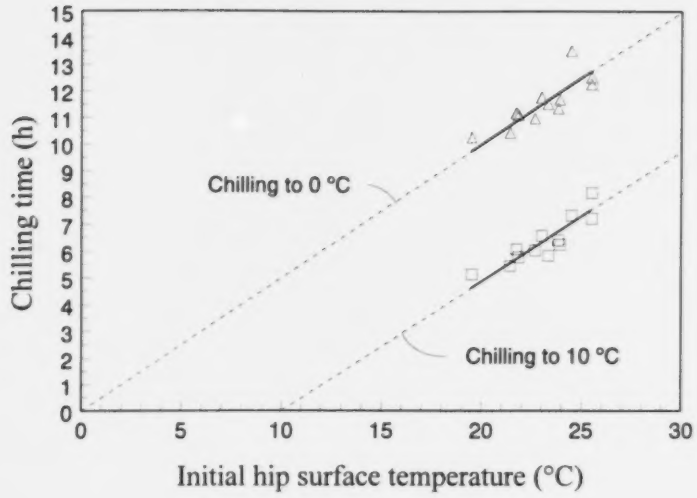

Figure 29. Relationship between the initial temperature and time for the hip surface location to decline to 0 and 10°C for the PC1 process.

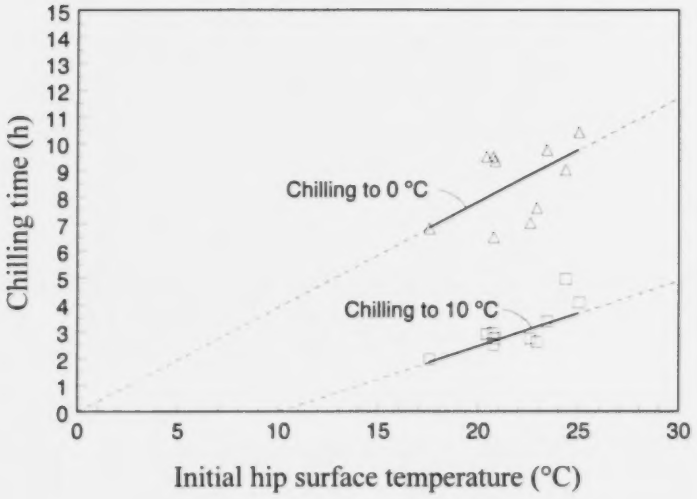

Figure 30. Relationship between the initial temperature and time for the hip surface location to decline to 0 and 10°C for the PC2 process.

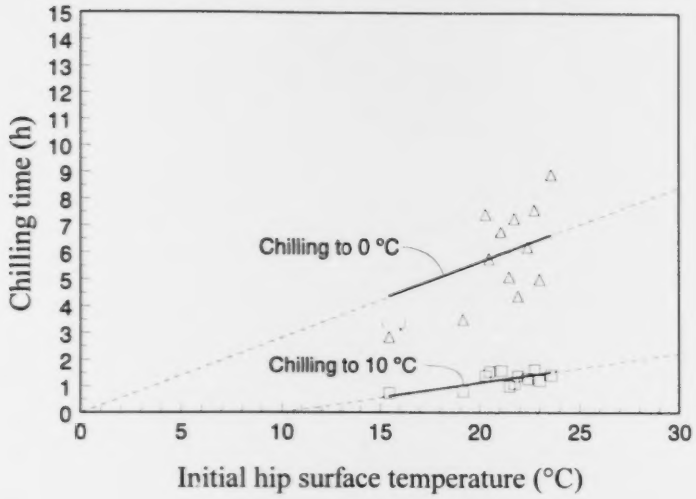

Figure 31. Relationship between the initial temperature and time for the hip surface location to decline to 0 and 10°C for the PC3 process.

Table 7. Experimental slope (γ) values from Eq. (13) for times required to chill sides to 10°C $(\theta_{10})^{\ddagger}$.

	PC1		PC2		PC3	
Muscle Location	γ ($h\ °C^{-1}$)	R^2	γ ($h\ °C^{-1}$)	R^2	γ ($h\ °C^{-1}$)	R^2
Loin Centre	0.324 [a] (0.007)	0.354	0.225 [b] (0.008)	0.266	0.149 [c] (0.007)	0.249
Loin Surface	0.453 [a] (0.014)	0.591	0.274 [b] (0.015)	0.487	0.145 [c] (0.014)	0.239
Hip Centre	0.655 [a] (0.007)	0.384	0.571 [b] (0.007)	0.135	0.553 [c] (0.007)	0.155
Hip Mid-Depth	0.490 [a] (0.009)	0.196	0.410 [b] (0.009)	0.088	0.352 [c] (0.009)	0.091
Hip Surface	0.488 [a] (0.009)	0.812	0.259 [b] (0.010)	0.546	0.115 [c] (0.009)	0.512
Neck Centre	0.493 [a] (0.009)	0.034	0.396 [b] (0.010)	0.083	0.375 [b] (0.009)	0.044

‡ Numbers in brackets are standard errors. R^2 is the coefficient of determination.

a-c Results given in rows bearing different letters differ significantly ($p<0.001$).

Table 8. Experimental slope (γ) values from Eq. (13) for times required to chill sides to 0°C (θ_0).‡

	PC1		PC2		PC3	
Muscle Location	γ ($h\ °C^{-1}$)	R^2	γ ($h\ °C^{-1}$)	R^2	γ ($h\ °C^{-1}$)	R^2
Loin Centre	0.386[a] (0.010)	0.288	0.312[b] (011)	0.365	0.261[c] (0.010)	0.127
Loin Surface	0.454[a] (0.014)	0.479	0.349[b] (0.016)	0.348	0.257[c] (0.014)	0.113
Hip Centre	0.661[d] (n/a)	n/a	0.673[d] (n/a)	n/a	0.664[d] (n/a)	n/a
Hip Mid-Depth	0.652[d] (n/a)	n/a	0.650[d] (n/a)	n/a	0.639[d] (n/a)	n/a
Hip Surface	0.500[a] (0.016)	0.741	0.392[b] (0.017)	0.319	0.276[c] (0.016)	0.149
Neck Centre	0.618[d] (n/a)	n/a	0.630[d] (n/a)	n/a	0.578[d] (n/a)	n/a

‡ Numbers in brackets are standard errors. R^2 is the coefficient of determination.

a-c Results given in rows bearing different letters differ significantly ($p<0.001$).

d Result is an estimate from regression analysis and extrapolation.

PART II. MEAT QUALITY

Uniformity of experimental beef sides

No differences ($p > 0.10$) in the means of live animal mass, trimmed side mass, and LT-pH_{45} of beef sides amongst treatments shortly after slaughter were detected (Table 9). The mean pH_{45} of the LT for sides assigned to PC1 chilling was significantly different from that of its control group ($p \leq 0.05$), but this difference was relatively small (i.e., 6.65 vs. 6.59). Similarly the average pre-ES temperature of the LT muscle (38.5°C) did not vary amongst treatments. Furthermore, the recorded differences in the fat layer measurements surrounding the rib-eye were not found to be significantly different ($p>0.12$). The average rib-eye areas for all treatments were approximately 70 cm^2, and did not differ greatly between treatments. Electrical stimulation reduced the average LT pH by 0.37.

Subjective quality assessments

With the exception of marbling scores, overall differences in meat quality as determined by subjective assessments were not evident (Table 10). The average marbling score for conventional chilling was greater than that for the PC1 and PC3 treatments ($p\leq0.07$), but the magnitudes of those differences (17 and 14) were found to be smaller than the numerical increment of the marbling scale (100). Differences in muscle score, quality grade, and yield grade were due almost entirely to animal variability, and could not be attributed to chilling treatment. Muscle scores ranged from 1 to 3 with most scores being either 1 or 2. The quality grade was predominantly AAA with a few sides being

graded AA, while yield grades ranged from Y1 to Y3. The subjective colour of each rib-eye grading site, with few exceptions, was assigned a value of 1.

Table 9. Mean carcass characteristics for assigned chilling treatments as determined on the kill floor prior to chilling, after chilling (24 h postmortem), and after extended cold storage (6 d postmortem).

	Chilling Program			
Carcass characteristic	**PC1**	**PC2**	**PC3**	**Control**
Steer live weight‡ (kg)	515.0 (4.3)	504.6 (4.6)	514.6 (4.3)	511.9
Trimmed side mass‡ (kg)	151.67 (0.38)	149.13 (0.31)	150.31 (0.61)	150.92
Dressing percentage (%)	58.9	59.1	58.4	59.0
24 h side masses‡ (kg)	150.12 (0.37)	148.08 (0.54)	148.58 (0.61)	149.03
6th day side masses‡ (kg)	149.64 (0.44)	146.87 (0.65)	147.40 (0.70)	148.36
Pre-ES temperature of the LT‡ (°C)	38.36 (0.10)	38.70 (0.07)	38.22 (0.08)	38.52
Pre-ES pH of LT muscle‡ (45 min postmortem)	6.645 * (0.024)	6.580 (0.024)	6.628 (0.027)	6.590
post-ES pH of LT muscle† (~50 min postmortem)	6.28 (0.033)	6.23 (0.035)	6.27 (0.033)	N/A
Change in pH of the LT due to electrical stimulation	-0.37	-0.37	-0.36	N/A

‡ Numbers in brackets are standard errors based upon comparisons between control and treatment results. The reported mean for the control result is an overall value, and is not the same as the mean result calculated for control versus experimental treatment comparisons.

† Numbers in brackets are standard errors based upon comparisons amongst treatment results.

* Result is significantly different from that of the control treatment ($p \leq 0.05$).

Table 10. Mean rib-eye steak characteristics associated with each chilling treatment from subjective and objective appraisals at 6th day postmortem.‡

	Chilling Program			
Rib-eye characteristic	**PC1**	**PC2**	**PC3**	**Control**
Average fat cover at top of rib-eye (mm)	12.833 (0.573)	13.182 (0.328)	15.417 (0.496)	13.8000
Maximum fat cover at top of rib-eye (mm)	14.583 (0.935)	14.545 (0.409)	18.917 (0.911)	16.829
Average fat cover at mid-point of rib-eye (mm)	11.917 (0.456)	11.364 (0.293)	13.167 (0.394)	11.571
Maximum fat cover at mid-point of rib-eye (mm)	12.667 (0.602)	12.182 (0.435)	14.250 (0.596)	12.429
Fat cover at bottom of rib-eye (mm)	10.417 (0.430)	10.455 (0.370)	11.833 (0.430)	11.000
Fat grade	9.894 (0.201)	9.273 (0.069)	10.250 (0.281)	9.943
Fat class	3.567 (0.120)	3.091 (0.201)	3.667 (0.136)	3.486
Cutability score	57.45 (0.15)	58.00 (0.35)	57.08 (0.26)	57.34
Rib-eye area (cm^2)	72.50 (1.27)	69.27 (0.75)	71.00 (1.06)	69.91
Marbling score	526.67 * (7.46)	500.91 (7.92)	530.00 * (13.38)	544.00

‡ Numbers in brackets are standard errors based upon comparisons between control and treatment results. The reported mean for the control result is an overall value, and is not the same as the mean result calculated for control versus experimental treatment comparisons.

* Probability of no significant difference between result and corresponding result for CON ≤0.07.

Objective quality assessments

With respect to objective measurements of rib-eye characteristics, substantial differences amongst treatments were largely not evident. Certain differences in water holding capacity (WHC), pigmentation, and protein degradation appear to have resulted from the differences in early chilling temperature history between treatments, as indicated by observed differences in protein solubility, steak drip loss, and objective colour (Table 11). The pH of conventionally chilled sides at the LT was reduced to an ultimate 6-d value (pHu) of 5.55, which was not significantly different from results for PC1 and PC2 ($p>0.12$). The pHu results for sides from PC3 and conventionally treated sides were significantly different ($p<0.01$), but the difference was not large (Table 11).

Protein solubility

Significant differences were found in protein solubility between results for conventional chilling and both PC1 and PC3 chilling ($p\leq0.05$), and between results for PC1 and PC3 ($p\leq0.05$). Protein solubility was highest in conventionally treated sides (207.7 mg g^{-1}) and was progressively lower for PC3, PC2, and PC1 (202.0, 195.5, and 193.2 mg g^{-1}, respectively).

Steak drip

Average LT steak drip loss was greater in sides chilled by the experimental treatments than those chilled under conventional conditions, but only the results associated with the PC1 and conventional treatments differed significantly (1.32%; $p\leq0.001$).

Table 11. Effects of chilling treatment on objective quality measurements.‡

Measurement	Chilling Treatment PC1	PC2	PC3	Control
Myofibrillar Fragmentation Index; 40-minute (% retained)	8.46 (1.27)	8.46 (1.33)	7.59 (1.27)	8.70
Myofibrillar Fragmentation Index; 24-hour (% retained)	4.36 (0.33)	4.31 (0.35)	4.14 (0.33)	4.40
Sarcomere length (μm)	1.645 (0.044)	1.641 (0.031)	1.705 (0.044)	1.679
Fibre width (μm)	96.653 (2.801)	86.818 (3.268)	98.995 (4.649)	93.615
Protein Solubility (mg g^{-1})	193.23[a] (1.67)	195.48[a,b] (2.78)	201.97[b,d] (2.31)	207.70[d]
Maximum shear force (kg)	5.239 (0.368)	4.993 (0.280)	5.195 (0.239)	5.277
Energy to yield point (kJ)	18.979 (1.308)	18.517 (1.548)	20.554 (1.277)	18.522
Rib-eye steak drip loss (%)	8.15[a] (0.27)	7.49[a] (0.36)	8.09[a] (0.45)	6.83[d]
Ultimate pH (6th day)	5.525[c] (0.014)	5.524[c] (0.013)	5.521[c] (0.009)	5.554[d]
C.I.E. Colour:				
L* (lightness)♣	38.667[a] (0.214)	38.130[a] (0.300)	37.503[a,d] (0.307)	39.967[d]
a* (red -- green)♣	19.894[a] (0.204)	19.273[a,d] (0.204)	18.958[a] (0.163)	18.734[d]
b* (yellow--blue)♣	9.867[a] (0.136)	9.427[a,d] (0.149)	9.439[a] (0.131)	9.212[d]
Chroma $\{(a^{*2}+b^{*2})^{1/2}\}$	22.209[a] (0.239)	21.459[a,d] (0.244)	21.064[a] (0.193)	20.846[d]
Hue angle {arctan (b*/a*)}	0.460 (0.003)	0.460 (0.003)	0.457 (0.004)	0.456

‡ Numbers in brackets are standard errors.
The reported mean for the control result is an overall value, and is not the same as the mean result calculated for control versus experimental treatment comparisons.

a - d Least square means bearing different letters differ significantly ($p \leq 0.05$)

♣ Psychometric colour values range from +60 to -60.

C.I.E. Colour

Conventional and PC1 chilling methods were significantly different ($p \leq 0.005$) in psychometric L*, a*, and b* terms, and in the derived chroma term. This was also true for L* results between conventional and PC2 chilled muscle ($p<0.03$); and for a*, b*, and chroma results between conventional and PC3 chilled muscle ($p<0.04$). Thus PC1 and PC2 chilled LT muscles were slightly darker than conventionally chilled muscle. The PC3 chilled muscle was also darker (mean L*) than conventionally chilled muscle, but the difference was not significant ($p=0.13$). The PC1 and PC3 chilled LT muscles exhibited stronger reddish (a*) and yellowish (b*) hues than conventionally chilled muscle. PC2 chilled sides also exhibited higher mean a* and b* values than conventionally chilled sides, but these differences were not significant ($p>0.60$). The results for a* and b* were reflected in significantly higher chroma values for PC1 and PC3, in comparison to values for conventionally treated meat. However, differences amongst all treatments in the derived hue angle were not significant ($p>0.13$).

Myofibrillar fragmentation index

It is noteworthy that standard error (SE) values for the 24 h MFI results were relatively low compared to those of the 40 min MFI results (e.g., $SE_{(MFI\text{-}24\ hr.)} = 7.6\%$ of the mean PC1 value versus $SE_{(MFI\text{-}40\ min)} = 15.0\ \%$). However, this reduction in the standard error, which was due to an improvement in sample consistency through more complete sample drying, did not result in the ability to detect MFI differences between treatments.

PART III. PREDICTIVE MICROBIOLOGY AND HYGIENIC EFFICIENCY

As expected, all bacterial species were predicted to exhibit the greatest proliferation under the linear temperature decline-rate conditions of the PC1 program, and the lowest proliferation under the initially very rapid chilling conditions imposed by the PC3 program (Fig. 32). The average net proliferation of *Pseudomonas* spp. predicted to grow under the rapid chilling, PC3 treatment was found to be 34.8, 58.8, and 44.2% of that predicted for the PC1, PC2, and CON chilling conditions, respectively. Similarly, the predicted proliferation of *S. typhimurium* bacteria under PC3 conditions (on combined lean and fat surfaces) relative to growth under PC1, PC2, and CON conditions was 21.7, 46.1, and 95.6%, respectively. The results for *E. coli* were very similar to the those for *S. typhimurium*, with PC3 chilling conditions producing 21.4, 46.5, and 99.4% proliferation relative to that for the other conditions. Conventional chilling resulted in a wider difference in 20 h predicted proliferation results amongst species in comparison to the experimental chilling treatments. It is particularly noteworthy that *Pseudomonas* spp. were predicted to be actively growing at the end of chilling because surface temperatures remained well above -2°C at that time. The predicted error in 20 h bacterial growth arising from surface temperature variation, (estimated by predicting bacterial growth rates associated with temperature profiles one standard error from the average surface temperature profile), was lowest for PC3 chilling (Fig. 32). Reflecting the lower variation in surface temperatures associated with the PC3 program, absolute variation in bacterial growth was least under the PC3 program.

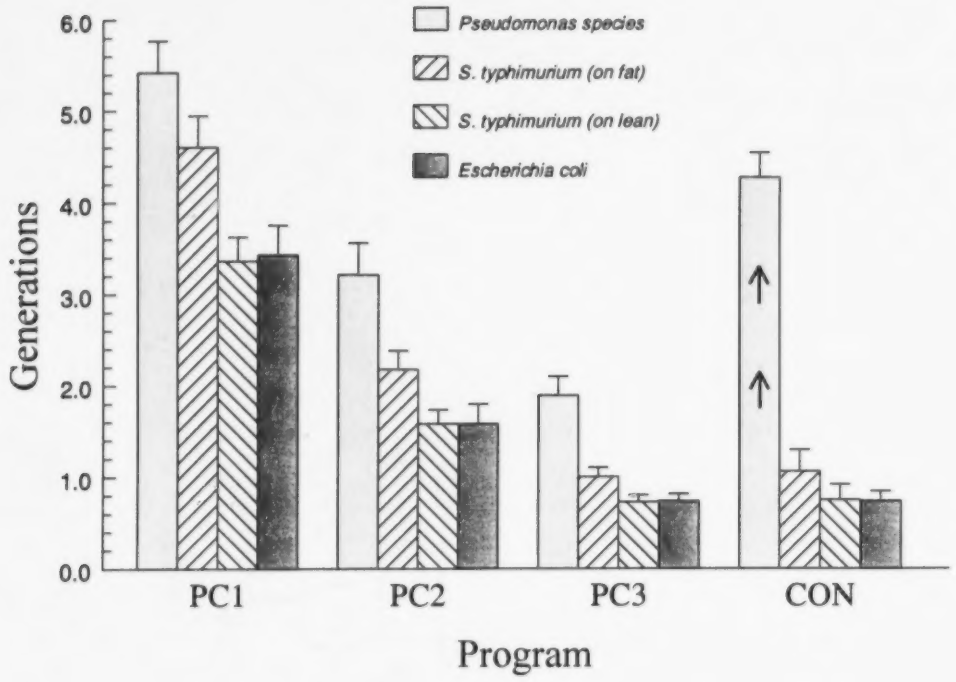

Figure 32. Predicted proliferation of selected bacterial species known to cause meat spoilage and risk to human health (up-arrows signify continued logarithmic growth after the 20 hour chilling period).

PART IV. CARCASS MOISTURE LOSSES

No significant differences ($p>0.05$) were observed amongst processes in terms of **overall** shrink that occurred during chilling (Table 12). The twenty four hour shrink was in the range 1.13 to 1.23 %. Shrink that occurred during conventional chilling was the highest by a small but insignificant amount ($p>0.1$). This result was confirmed twice, once using data obtained with the abattoir scale, which was used to measure side masses on entry and exit from the chillers, and again with the load cell used to monitor side masses throughout the chilling processes. Interestingly, moisture losses that occurred inside the sealed polyethylene containers over the five day holding period were greater than the evaporative losses.

Evaporation process model results

The predictions of the evaporation loss model were found to be in good agreement with the experimental results. This is graphically shown in Fig. 33 in which the predicted and measured results are compared for a single process run. The correlation coefficient (R^2; Kvalseth, 1985) was dependent upon the degree of logarithmic smoothing (i.e., smoothing radius) used to help resolve the mass loss history profile. As expected, the measured evaporation rate varied with the calculated moisture gradient between the carcass and surrounding air. In the absence of accurate data for the air velocity distribution near and over the external carcass surface, it was arbitrarily assumed that the average velocity of the undisturbed air surrounding the carcass (outside boundary layer) was reduced to 10% of that at the anemometer location in the air discharge opening over the carcass. If the true air velocity reduction factor (x%) were to be measured and found

to be different (i.e., $x \neq 10\%$), the value of β would need to be adjusted by the value $(10/x)^{1/2}$. Accordingly, the parameter β was estimated to be 0.111 ±0.007 with the parameter α set to a value of 0.5 (i.e., flow over a plate surface, $Re<3 \cdot 10^5$; Geankoplis, 1978). Experimental values of selected parameters and variables in Eqs. (5) through (12) are reported in Table 13.

The evaporation model was used to investigate the theoretical effects of chilling program choice on the evaporation loss histories associated with each program, using the mean carcass and environmental histories as input to the model. Results of that analysis are depicted in Fig. 34, in which the changing evaporative losses for each of the three programs are plotted against process time. These model results indicate that the evaporation rate was initially ($0 < \theta_c < 4$ h) highest for PC3 and lowest for PC1, but that overall evaporation was highest for PC1 and least for PC3 over the 20 hours. However, these overall evaporation values were low, and the measured results did not differ ($p>0.10$).

Table 12. Carcass moisture losses during various stages of processing and drying rates during chilling.‡

	Chilling Program			
Measurement	**PC1**	**PC2**	**PC3**	**Control**
Moisture loss over 20 h chilling (chiller scale) (%)	1.049	1.031	1.025	1.071
Moisture loss over 24 h chilling (abattoir scale) (%)	1.136 (0.045)	1.133 (0.044)	1.147 (0.043)	1.229
Side drip loss during 5 days of cold storage (%)	1.501 (0.059)	1.460 (0.079)	1.475 ** (0.056)	1.533
Maximum rate of moisture loss (% h-1)	0.1126	0.1677	0.1734	-
Mean rate of moisture loss (% h-1)	0.0522	0.0513	0.05100	-
Drip loss from packaged rib-eye steak (%)	8.15 * (0.27)	7.49 (0.36)	8.09 (0.45)	6.83

‡ Numbers in brackets are standard errors based on comparisons between treatment and control. The reported mean for the control result is an overall value, and is not the same as the mean result calculated for control versus experimental treatment comparisons.

* Probability of null difference between result and corresponding result for CON ≤0.05.

** Probability of null difference between result and corresponding result for CON ≤0.07.

Table 13. Estimated values of parameters and variables for evaporation rate model (α=0.5). ‡

	Chilling Program			
Model parameter or variable	**PC1**	**PC2**	**PC3**	**Combined**
A_S (m^2)	3.663 (0.015)	3.623 (0.030)	3.600 (0.049)	3.629 (0.020)
$\frac{V_s^2}{A_s^3}$ x 10^{-4}	4.482 (0.068)	5.067 (0.408)	4.458 (0.118)	4.637 (0.130)
Re x 10^{-4} *(20 hour mean)*	7.606 (0.168)	7.547 (0.101)	7.618 (0.113)	7.594 (0.075)
β	0.103 (0.005)	0.105 (0.013)	0.124 (0.008)	0.111 (0.005)

‡ Numbers in brackets are standard errors.

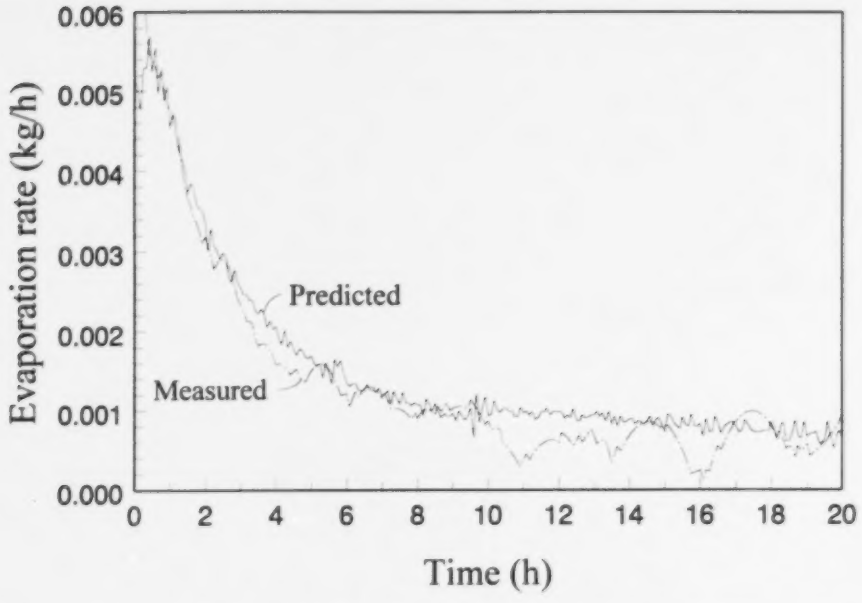

Figure 33. Predicted and measured evaporation rate versus time for one chilling run operating under the PC3 program (R^2 = 0.93).

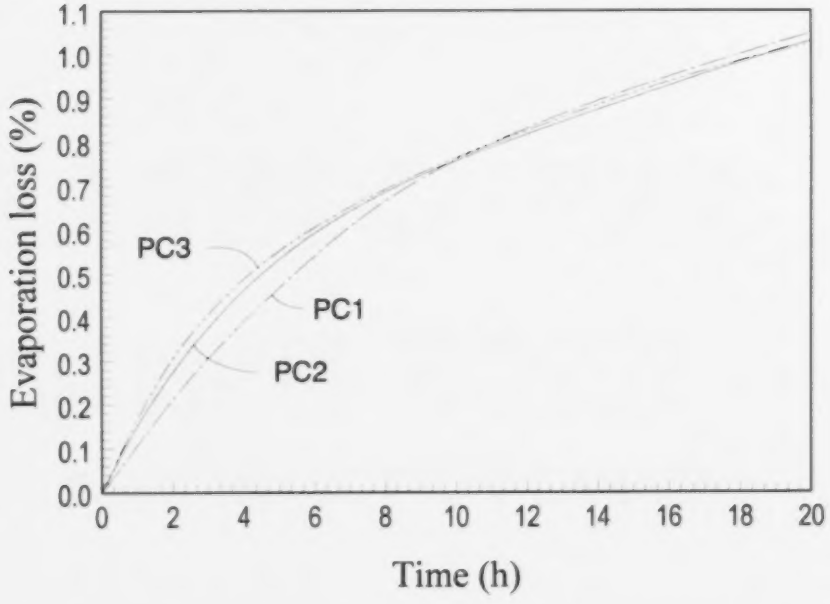

Figure 34. Predicted carcass moisture loss due to evaporation for three chilling programs.

Chapter V

DISCUSSION

Defrost frequency and evaporative shrink

The defrost frequency, which might readily be assumed to be proportional to the rate of frost accumulation, was found to be highest for the PC3 process and least for the PC1 process. This would appear to contradict the results showing no difference in evaporative shrink over (20 h) due to the chilling program. This would also seem to be inconsistent with other studies (Drumm *et al.*, 1992b, 1989a; Gigiel *et al.*, 1989) which have indicated an inverse relationship between chilling rate (i.e., carcass temperature decline rate) and carcass shrink. This apparent anomaly is likely explained by the fact that air temperatures were above 0°C during the initial period of each process, and this period was shortest for PC3 and longest for PC1. Thus, the more aggressive the chilling program was initially, the longer the period during which air temperature was below freezing. As revealed in the loin surface temperature profiles of Fig. 20 and the hip surface temperature profiles of Fig. 21, the time for beef-side surface temperatures to fall to sub-zero levels was, as expected, reduced by the application of a high chilling rate early in the process. Earlier freezing of the carcass surface, thereby sealing moisture within the carcass, might provide an explanation for the reduced shrink that has been reported for other "rapid chilling" processes, and possibly the slightly reduced shrink (if any) observed in this study. Thus it is likely that the initially more aggressive PC3

process demanded a higher number of defrost events simply because heat exchanger frosting occurred earliest in that process.

Carcass temperature control error

The small, increasing control error trend (i.e., control drift) that occurred during processing likely reflects the changing responsiveness of the average carcass temperature to control actions as the heat transfer potential between the carcass and its surroundings declined over time. The temperature difference between the carcass surface and the surrounding air declined during the chilling process such that any incremental change brought about in that temperature difference by a control action that is proportional to the instantaneous and integrated error would have thus had a different relative impact at different times during the process. While this drift was relatively insignificant, improved control error could probably be achieved by calculating the control gain value as a function of both the feed-back error signal and the instantaneous temperature difference between the beef side and the surrounding air.

If precise control of an individual muscle temperature history is desired, the same procedures as were used in this study could be employed, with much reduced temperature variability in the muscle of interest, by narrowing the temperature measurements to the muscle or carcass region of interest. This approach would be useful, for example, in the development data concerning kinetics of meat quality for specific cuts of meat.

Variation in muscle temperature history

Some of the observed variation in temperature history for each muscle location was linked to beef side orientation in the chiller and to the initial muscle temperatures. However, the unexplained portion of this variation must be attributable to other uncontrolled factors which impact on the transient thermal response of the beef side, such as, for example, carcass mass, shape, and fat cover. Although these factors, including initial temperature distribution and carcass orientation, likely cannot be practically or economically controlled in commercial enterprises, they might be taken into account when establishing temperature-time exposures. For example, in a line-chilling operation, carcass characteristics could possibly be quickly measured prior to chilling, and used to determine or adjust the subsequent line chilling conditions. This would require a systematic study of the interactive effects of carcass factors and the temperature-time program selections of interest. Moreover, an analysis of the thermal responses of carcasses relative to their masses, shapes, and sizes of this study would provide little information due to the relatively small variation of these variables.

Model for continuous line-chilling system

The controlled chilling system described herein could serve as a development tool for the design of a line-chilling system for beef or other large-animal carcasses. Very simply, the observed air temperature response profiles of each control program provide design temperatures for each stage of a hypothetical chilling tunnel. For the programs studied, the observed air temperatures tended to change with time on a gradual basis. Therefore, to implement these air temperature profiles in a chilling tunnel system would

require a control strategy involving adjacent control zones, possibly with the provision for gradual, rather than sudden, air temperature changes between such zones. That is, discrete air temperature control would be required within each control zone or defined tunnel section, but some provision might be necessary to control blending of temperatures at the interface between these zones.

It was observed that the lowest air temperature required during each of the studied processes occurred towards the end of each process, and air temperature tended to decline along with the average carcass temperature (i.e., particularly for PC1). Implementation of this declining-air temperature history in a line-chilling system could possibly be best accomplished by allowing air movement through the tunnel in a direction that is counterflow to the carcass movement. Such an arrangement could be highly efficient since the air chilling requirement could possibly be carried out mainly at the exit end of the tunnel. This strategy would obviously demand careful consideration of design factors such as airflow circulation rate and the application of energy conservation measures. A potential hygienic advantage of such a counterflow air passage strategy would be the ability to only use fresh supply air for chilling purposes, without the need for re-circulating moisture-saturated air that may have become contaminated from repeated carcass exposures. This follows from the fact that the exhaust air (i.e., Ta(0)) would likely be warmer than ambient air in most North American locations.

In programs such as PC1, which affect a constant, low rate of carcass temperature decline during the early chilling stage, the final air temperature must be lower to

compensate for the unfulfilled chilling requirement remaining during the latter stage. However, for the PC1 process, the required minimum temperature was less than 4°C lower than that required in the PC3 program. This small difference would certainly not preclude PC1 as a viable program choice within a commercial implementation of a line-chilling or multi-stage chilling scheme.

Program choice when ES is not used

With the application of ES, beef carcasses generally achieve full rigor by 4 h postmortem, whereas without ES this time is in the range of 15-20 h (Greaser, 1986). If ES were *not* to be applied in a line-chilling operation using one of the experimental chilling program choices presented herein, further consideration would need to be given to the pre-rigor times that muscles of interest remain above about 10°C, in view of cold-shortening concerns. None of the described chilling treatments maintained loin centre temperatures above 10°C for more than about 9 hs, although deep hip and neck centre temperatures remained above 10°C for about 17 and 14 h, respectively (PC1, Table 4). However, θ_{10} for the loin centre location associated with PC3 chilling was comparable to that for conventional chilling. Therefore, if ES were not used with any of the experimental programs, cold-shortening effects would likely not be greater than anything observed in conventionally chilled beef.

Meat quality

With the exception of protein solubility, the estimable quality differences were primarily between conventional and one or more of the experimental chilling treatment

results. The 20 h loin temperature history associated with each experimental treatment was measured and found to be unique (Figs. 20 and 22), yet meat quality differences were mostly not observed amongst these treatments. This may be partly explained by the fact that in all experimental treatments loins began to freeze within the 20 h chilling period, and their centre temperatures all declined to a stable value of about -1.0°C, several hours before 20 h had elapsed (Fig. 22). In contrast to this, conventionally chilled loins remained above 0°C at 22 h (Fig. 19), and for an extended period beyond that time (based on extrapolation, the unaccomplished chilling in other parts of the carcass, and the relatively high, constant air temperature). Thus, the different results in colour and steak drip loss obtained for the experimentally chilled beef (compared to conventionally chilled) possibly resulted from the application of ES, or the lower loin temperature that was developed and maintained from an early time, or possibly the combination or interaction of these factors

The colour differences that were measured would probably not be detectable by consumers, nor be of any commercial significance. Nonetheless, the results support other studies showing that rapid chilling produces darker meat (Jones *et al.*, 1986; Faustman and Cassens, 1990; Lanier *et al.* 1977). That any colour differences were observed, however, may be remarkable because no differences in pHu and LT temperature between treatment results were observed when colour was measured after six days. Long-term differences in colour due to ES apparently do not exist, in any case. In one study, Ledward *et al.* (1986) demonstrated that colour in the LD was not influenced by ES. In another study in which sides were blast chilled (-30°C, 3 h), Aalhus *et al.* (1994) found

that ES had no effect after 6 days on the colour of SM, and produced differences of only 0.6 and 0.4 in a* and b*, respectively on LT muscle, with no ES effect on L*.

Also, changes in colour (following sample exposure to air) after the development of full rigor, and after 24 h (say) appear to be negligible or non-existent. Mallikarjunan and Mittal (1994c) demonstrated that increases in beef lightness (C.I.E. L*) after 8 h postmortem under conventional chilling conditions (0°C, 75-95% RH) are not significant, although other changes in colour (e.g., a*-redness) could occur after 24 h. Although their study covered a 50 h postmortem period only, Mallikarjunan and Mittal's (1994c) results suggest that colour measured after 6 days of chilled storage would be virtually the same as that measured after about 24 h. Thus it is more likely that the observed differences in colour resulted from differences in the loin temperature histories during the first 24 h. Hypothetically, the darker meat of the experimentally chilled beef may have resulted from the early suppression of oxygen-consuming enzymatic processes, leaving the LT muscle at 6 d postmortem with a greater (conserved) capacity to absorb oxygen following exposure.

In any case, other research has demonstrated that meat colour is improved as its temperature is reduced (Faustman and Cassens, 1990; Lanier *et al.*, 1977; Hood, 1980). Conversely, maintaining beef at higher temperatures accelerates pigment oxidation by increasing rates of pro-oxidant reaction within the tissue (Kropf, 1993). Thus, the early reduction of muscle temperature would appear to favour the extension of shelf life, in respect of colour stability.

Steak drip loss was significantly higher in PC1 chilled LT steaks than in conventionally chilled steaks. This indicated lower WHC may have been caused by partial freezing of bound water during the latter stages of chilling, and by its subsequent thawing as the beef side equilibrated in the holding cooler over 5 days. The loss of WHC due to freezing and thawing of meat is well known, and has been extensively reviewed by Hamm (1986). According to Hamm, the effects of freezing and thawing on WHC are complicated by factors which influence the formation and size of intracellular and extracellular ice crystals, and water diffusion or movement across cell membranes during freezing and thawing processes. For example, freezing or thawing velocity, or both, and factors such as frozen-storage temperature and time appear to influence the size and location of ice crystals, and the manner in which they ultimately disperse within the meat tissue. Although such considerations were beyond the scope of this study, it is known that a slow meat freezing rate tends to result in more drip loss following thawing than quick freezing. Freezing of water in muscle begins to occur at -1^{o}C, which was observed in the loin centre location in all chilling programs (Fig. 19). Moreover, the PC1 chilling program produced the lowest rate of muscle temperature decline in the period leading up to the development of sub-zero temperature. Subsequently, PC1 chilling resulted in the lowest air and meat surface temperatures of all treatments. Whether the slower initial loin temperature decline rate of the PC1 program resulted in a lower freezing velocity is difficult to determine, since the temperature distributions between the loin surfaces and centres were not determined. Nevertheless, the fact that the PC1 loin was reduced to the lowest sub-zero temperature may help to explain its lower WHC.

A possible other, or additional explanation for the lower WHC (reflected in the steak drip losses) of PC1 chilled loin may be related to the effect of ES on early postmortem pH decline. Loins from the PC1 process were also lowest in protein solubility, which likely reflects a lower pH condition while the loin temperature remained warm, brought about by the combination of ES and slow chilling (elevated pre-and post-rigor temperature). It is perhaps noteworthy that the mean drip losses for all experimental (ES) treatments were higher, and the mean protein solubilities for these treatments were lower than the equivalent means for conventional chilling (although these results were only highly significant for the PC1 versus CON contrast *in both cases*). However, Aalhus *et al.* (1994) demonstrated no effect of ES on drip loss in beef SM and LT muscles subjected to blast chilling (-30°C, 3 h). Furthermore, they found that LT drip loss was slightly higher in conventionally chilled sides as compared to both blast-chilled and ES + blast-chilled sides. Thus, ES would not appear to have had much (if any) effect on drip loss. Also, because differences in drip loss were not observed between the experimental treatments, it is unlikely that the temperature-history differences had a direct effect on drip loss.

Unlike other quality indicators, protein solubility was found to vary amongst the experimental treatments, and was greatest for the conventional chilling, and increasingly lower with decreasing initial chilling rate (i.e., θ <~2 h). The fact that PC3 produced a higher soluble protein than PC1 suggests that early temperature history played a significant role in irreversible processes such as proteolysis, or denaturation, or alteration of protein-protein interactions, or all of these. This hypothesis may be supported by the

fact that conventional chilling (highest early chilling rate) produced higher protein solubilities than either PC2 or PC1 (lowest chilling rates), although ES might account for part or all of this difference. Nevertheless, despite the protein solubility differences, no differences were found in terms of tenderness, such as might have been indicated by MFI or shear values. Thus, any differences in the protein composition or LT muscle ultrastructure due to chilling program choice would not likely translate into commercially significant tenderness differences.

Chapter VI

Summary and Conclusions

A research system for studying numerous effects of specific temperature decline profiles in large animal carcasses was successfully developed. The system was capable of continuously chilling a 125 kg beef side from the slaughter floor from an average temperature of 33.3°C to an average of 0°C along different temperature-time trajectories. The system chilled beef sides to within 0.25°C of a specified, time-varying target average side temperature. The precision of the temperature control system was limited by the measurement resolution of the RTD sensors used to measure the average carcass temperature. The control system was capable of maintaining the absolute deviation between the target and monitored average carcass temperature to a mean value of 0.11 (±0.04)°C or less when operating under the experimental chilling programs of this study.

The research system effectively utilized a reserve of pre-chilled working fluid (i.e., aqueous propylene glycol) to avoid the necessity of providing a larger refrigeration compressor having a chilling capacity matched to the peak transient thermal load imposed by the system and enclosed carcass(es). Accurate control of the average side temperature was maintained throughout the experimental processes despite transient increases in the temperature of the working fluid, particularly during the early (peak load) stages of chilling, and despite the periodic need to defrost the operative heat exchanger surfaces.

Whereas the system to control the average carcass temperature was proven to be highly effective, between-run variation in the individual muscle temperature histories of beef sides subjected to the same process was observed. Much of this variation was attributed to random variability in the initial temperatures of each muscle location at the start of chilling. It was found that increasing the chilling rate early in the overall process reduced variability in the time required for individual muscles to decline to 10 and 0 °C. However, increasing the chilling rate also had the effect of reducing temperature uniformity during the 20 h process.

With respect to the experimental chilling programs that were investigated, the average-temperature decline history of the carcass was found to influence processing attributes of commercial interest. Firstly, the carcass temperature history (or chill program) was confirmed to be an important determinant of carcass hygiene. Rapid carcass chilling in the early stages of chilling dramatically reduced bacterial growth potential on carcass surfaces during subsequent chilling and storage. Compared to the experimental programs, conventional chilling provided the most rapid chilling conditions in the first two hours, but its subsequent, low chilling rates were inadequate to restrict the ongoing proliferation *pseudomonas* spp. after 20 h. This problem, did not exist in the experimental chilling programs because the average carcass surface temperatures fell below the lower threshold for growth of that species.

As well, accelerating the rate of carcass cooling reduced the sensitivity of chilling times (e.g., θ_{10}, θ_0) to the variable carcass temperature condition found to exist at the

beginning of chilling. At the same time, rapid initial chilling generally resulted in a wider internal temperature distribution, throughout the chilling process. Thus, with respect to the time for a specific muscle to reach a desired temperature, a reduction in the temporal variation (rapid chilling) will be accompanied by an increase in the spatial temperature variation at that location.

Differences in meat quality of LT muscle (12-13th rib), of electrically stimulated beef sides due to average carcass temperature history during chilling were only evident in terms of protein solubility, and were likely of no commercial significance. Psychometric colour (C.I.E. L*, a*, b*) differences between conventionally chilled and experimentally chilled beef were evident, but such differences would not likely be of commercial significance. Steak drip loss was slightly higher in LT meat from sides subjected to a substantially linear average-carcass temperature decline-rate process (PC1) than in meat chilled conventionally. Subjective quality attributes of the processed beef were within acceptable limits, and there was no evidence that the average carcass temperature influenced subjective results.

With respect to economic moisture losses, evaporation rates varied with the chilling rate, but carcasses identically chilled to a 0^{o}C temperature end-point at 20 h experienced the same average rate of evaporation (regardless of carcass temperature history). The net evaporative chiller shrink was 1.0% of side mass. Drip losses from suspended, sealed sides held in refrigerated storage over 5 days following chilling was approximately 1.5%, and no differences in such drip were observed amongst the three

experimental chilling treatments. The carcass drip loss was possibly higher in conventionally chilled beef than in beef subjected to the PC3 (initially very rapid chilling) program ($p=0.07$).

In consideration of the processing and meat quality attributes investigated in this study, and from amongst the four chilling programs proposed, the best line-chilling process is the PC3 program. This follows primarily from the fact that this process produced the lowest potential for bacterial growth yet produced no detrimental effects on meat quality, did not increase cooler shrink, nor cause any increase in drip losses from stored sides and steaks. Moreover, while moisture loss differences were not indicated to be significant ($p<0.05$), the conditions of the PC3 regime may have caused modest reductions in cooler shrink and purge from the suspended post-chill sides.

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APPENDICES

APPENDIX I

COMPUTER MODEL OF THE PERFORMANCE

OF A TWO-STAGE CHILLING SYSTEM

USED TO

ESTIMATE DESIGN HEAT TRANSFER CAPACITIES

Refrigeration System Estimated Loads - Beef Carcass Chilling

Input data: $A := READPRN(out250)$

Time (h):

Heat removal from carcass vs time from simulation (kJ/m^3): $EN := (A)^{<1>}$ $tme := A^{<0>}$

Estimated beef carcass hip centre temperature (Celsius): $Tc := A^{<2>}$ $h := tme_{(2)} - tme_{(1)}$

Estimated beef carcass surface temperature (Celsius): $Ts := A^{<3>}$ $h = 0.1$

Air temperature profile (Celsius): $Ta := A^{<4>}$ $n := last(Tc)$

$n = 201$

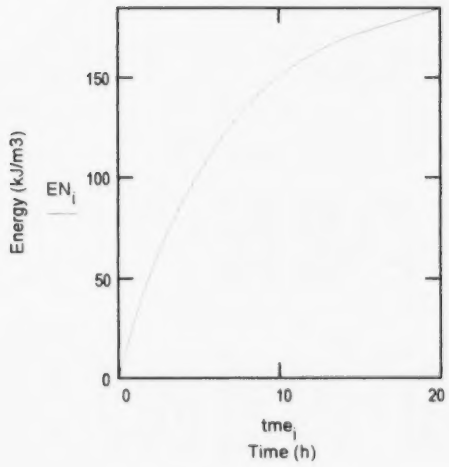
Dressed carcass weight (kg): $W := 250.00 \cdot 2.0$

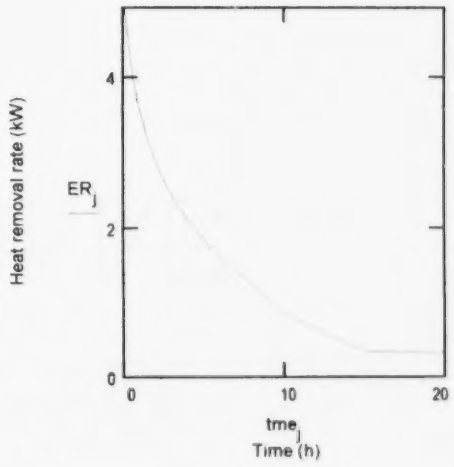
$tme_n = 20$

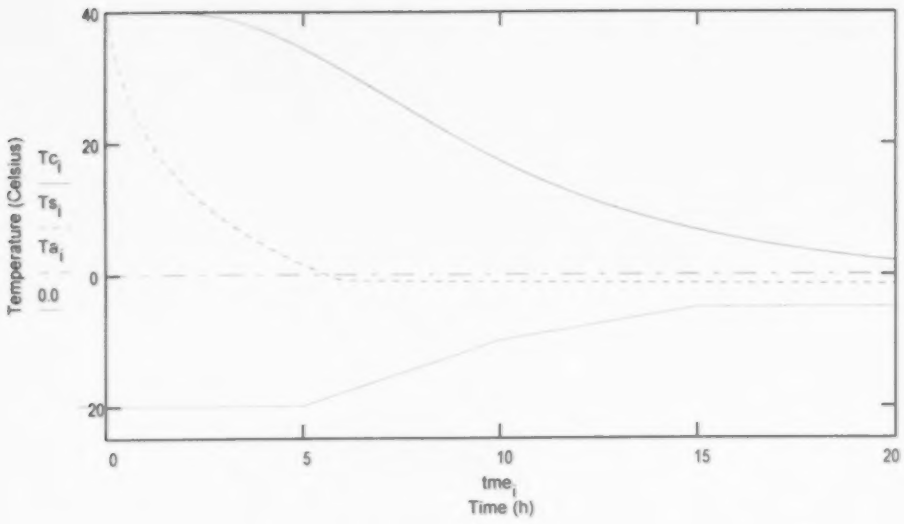
Heat removal rate: $ER_j := W \cdot \frac{EN_{(j+1)} - EN_{(j-1)}}{7200 \cdot h}$ $j := 1..(n-1)$ $i := 0..n$

$ENm := max(EN)$ $Emax := max(ER)$

$ENm = 183.787$ $(kJ/m^3\ total)$ $Emax = 4.8972$ (kW)







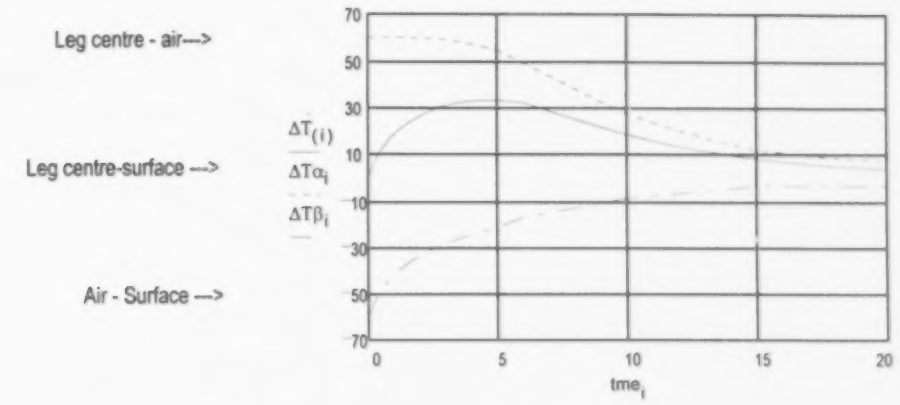
Predicted carcass temperature vs. chilling time

Legend:

W = Carcass weight (kg)
h = Time increment used in numerical solution (h)
tme = Time from onset of chilling (h)
EN = Thermal energy released from carcass (kJ/kg)
ER = Heat flux from carcass (kW)
Tc = Temperature of centre of leg (C)
Ts = Temperature of surface of leg (C)
Ta = Average carcass temperature (C)

Centre to surface temperature difference characteristic profile:

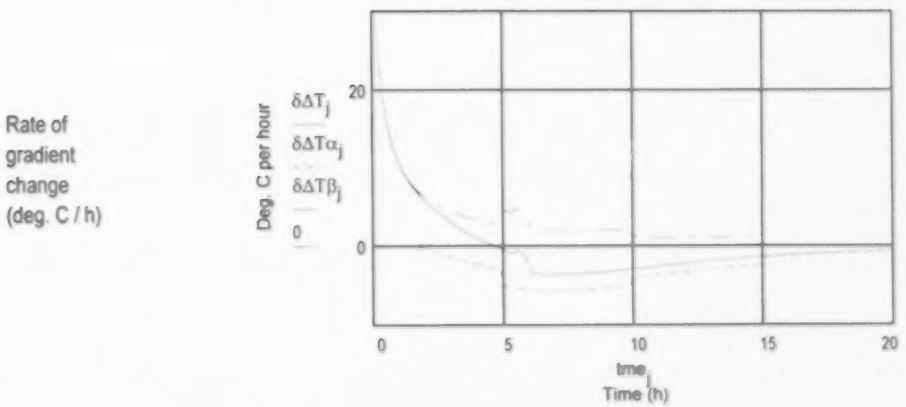
$\Delta T_i = Tc_i - Ts_i \qquad \Delta T\alpha_i = Tc_i - Ta_i \qquad \Delta T\beta_i = Ta_i - Ts_i$



Temperature Differences (gradients)

$$\delta\Delta T_j = \frac{\Delta T_{(j+1)} - \Delta T_{(j-1)}}{tme_{(j+1)} - tme_{(j-1)}} \qquad \delta\Delta T\alpha_j = \frac{\Delta T\alpha_{(j+1)} - \Delta T\alpha_{(j-1)}}{tme_{(j+1)} - tme_{(j-1)}}$$

$$\delta\Delta T\beta_j = \frac{\Delta T\beta_{(j+1)} - \Delta T\beta_{(j-1)}}{tme_{(j+1)} - tme_{(j-1)}}$$



Specification of Reservoir / Refrigeration System Capacities:

Note: Solutions for
(0) = 60% glycol
(1) = 70% glycol

$Tayr = -20.0$ $\Delta Ts = 10.0$

$Tr_1 = Tayr - \Delta Ts$ $Tr_0 = Tr_1$ $Tr_0 = -30$

Specific Heats for 60% and 70% propylene glycol

Time increment: $hs = h \cdot 3600.$ $hs = 360$

$\Delta Cp_0 = 3.360 - 3.284$ 60% p.g.

$\Delta Cp_1 = 3.117 - 3.012$ 70% p.g.

$$Cp_0 = 3.284 + \left(\frac{\Delta Cp_0}{40.0}\right) \cdot (Tr_0 + 27.7778) \qquad Cp_1 = 3.012 + \left(\frac{\Delta Cp_1}{40.0}\right) \cdot (Tr_0 + 27.7778)$$

$Cp_0 = 3.2798$ kJ/kg C (60% p.g.) $Cp_1 = 3.0062$ kJ/kg C (70% p.g.)

$Cpg = Cp_1$ Propylene glycol spec. heat at initial temperature.

$\Delta Ts = 10$ *Specified initial propylene glycol - air temp. difference*

$fr = 0.75$ *Specified design fraction of initial load supported by refrigeration.*

$fm = 0.55$ *Specified design Reservoir mass / Carcass mass ratio.*

$\rho = 1.40$ Density of air (kg/cu. m)

$Ca = 1.005$ Specific heat of air (kJ/ kg C)

$\Delta Ta = 15 - Tayr$ Desired temperature drop of air & steel (C)

$\Delta\theta = hs \cdot 2$ Time period for air temperature drop (s) $\Delta\theta = 720$

$Va = 4 \cdot 2 \cdot 2$ Volume of refrigeration cabinet (cu. m) $Va = 16$

$Qa = \rho \cdot Va \cdot Ca \cdot \frac{\Delta Ta}{\Delta\theta}$ Heat load to chill initial air volume (kW)

$Qa = 1.0943$

$Cps = 0.450$ Specific heat of stainless steel (kJ/kg C)

$\rho s = 8.3$ Density of stainless steel (kg/cubic m)

$Vs = 2.0 \cdot (2 \cdot 2 - 2 \cdot 4 - 2 \cdot 4) \cdot 0.004$ Volume of stainless steel in walls, etc. (cubic m)

$Qs = \rho s \cdot Vs \cdot Cps \cdot \frac{\Delta Ta}{\Delta\theta}$ Heat load to chill initial steel volume (kW)

$Qs = 0.0291$

$Qc = 2.931$ Est. cabinet infiltration heat load (kW)

$Qlm = (Qa + Qc + Qs + Emax) \cdot 1.10$ Max. (initial) refrigeration load (kW) $Qlm = 9.8468$

$Qrm = fr \cdot Qlm$ Design capacity of R-22/ evap. system (kW).

$Mp = fm \cdot W$ Design mass of propylene glycol (kg). $Mp = 275$

$Ql_j = (ER_j + Qc) \cdot 1.10$ Time-varying predicted total heat load (kW)

$Qd_j = Ql_j - Qrm$ Time-varying refrigeration defecit (kW)

$Qd_0 = Qlm - Qrm$ Initial defecit, incl. chilling of air (kW)

$jn := 12$ $k1 := 1..jn$ $k2 := jn + 1..n - 1$ <---Timing indices

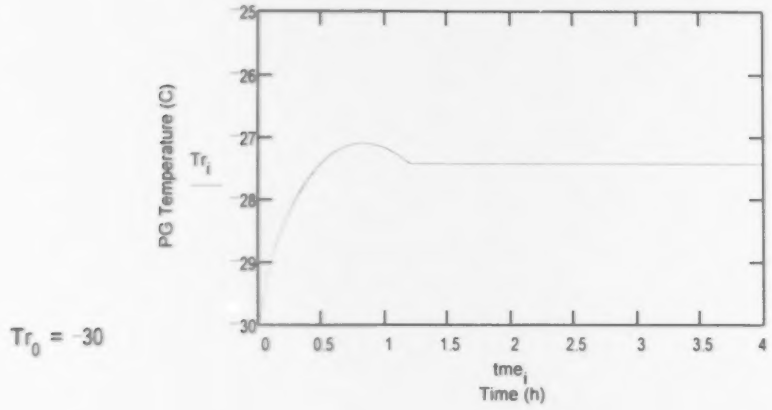
$$Tr_{k1} := Tr_{(k1-1)} + \frac{hs \cdot Qd_{k1-1}}{(Mp \cdot Cpg)} \qquad Tr_{k2} := Tr_{k2-1} \qquad Tr_n := Tr_{n-1}$$

$Tr_0 = -30$

$Tr_{jn} = -27.4344$

$Tr_i := if(Tr_i > Tr_0, Tr_i, Tr_0)$ $Tr_i := if(Tr_i > Tayr, Tayr, Tr_i)$

$Tmin := min(Tr)$	Minimum medium temperature (C)	$Tmin = -30$
$Tmax := max(Tr)$	Maximum medium temperature (C)	$Tmax = -27.1053$
$\Delta Tm := Tayr - Tmax$	Min. air-liquid temp. difference (C)	$\Delta Tm = 7.1053$



Predicted propylene glycol temperature versus time

Refrigeration and Reservoir Capacities:

(S.I. Units)

Refrigeration capacity (kW): $Qrm = 7.3851$
Maximum refrig. load (kW): $Qlm = 9.8468$

Refrigeration factor: $fr = 0.75$

Reservoir medium mass (kg): $Mp = 275$
Carcass weight (kg): $W = 500$

Mass factor: $fm = 0.55$

Initial medium temperature (C): $Tr_0 = -30$

Max. medium temperature (C): $Tmax = -27.1053$

Min. temperature difference (C): $\Delta Tm = 7.1053$

SI->English conversions:

$$hcf = \frac{3600.0}{1.0551} \qquad lcf = 3.2808 \qquad wcf = 2.2046226 \qquad tcf = 1.8$$

$Qlme = hcf \cdot Qlm$

$Qrme = hcf \cdot Qrm$

$Mpe = wcf \cdot Mp$

$We = wcf \cdot W$

$Tre = tcf \cdot Tr_0 + 32.$

$Tmxe = tcf \cdot Tmax + 32.$

$\Delta Tme = tcf \cdot \Delta Tm$

Refrigeration and Reservoir Capacities:

(Imperial Units):

Refrigeration capacity (Btu/h): $Qrme = 25197.8661$
Maximum refrig. load (Btu/h): $Qlme = 33597.1548$

Refrigeration factor: $fr = 0.75$

Reservoir medium mass (lb): $Mpe = 606.2712$
Carcass weight - 2 sides (lb): $We = 1102.3113$

Mass factor: $fm = 0.55$

Initial medium temperature (F): $Tre = -22$

Max. medium temprature (F): $Tmxe = -16.7896$

Min. temperature difference (F): $\Delta Tme = 12.7896$

Heat Exchanger (Chiller) Specification:

Duct width (m):	$Dw = 0.8128$	Air density (Ta=-20)	$\rho = 1.4$
Duct depth (m):	$Dd = 0.4064$	specific heat	$Ca = 1.005$
liquid/air flow fraction:	$fl = 0.35629$	Airflow area	$A = Dw \cdot Dd$
		velocity (m/s)	$v = 2.92$
Chill medium temp.: (see reservoir calc.)	$Tli = Tmax$	*outlet temperature*	$Tao = 25.0$
		Liquid Spec. Heat:	$Cpg = 3.0062$
Mass flowrate of air:	$\Phi a = \rho \cdot v \cdot A$	$\Phi a = 1.3504$ kg/s	$A = 0.3303$
	$MCa = \Phi a \cdot Ca$		$Voa = \frac{\Phi a}{\rho}$
Mass flowrate of liquid:	$\Phi l = fl \cdot \Phi a$	$\Phi l = 0.4811$ kg/s	
	$MCl = \Phi l \cdot Cpg$	$\Phi lm = \Phi l \cdot 60$	$\Phi lm = 28.8671$ Kg / min

$Carr_0 = MCa$ $Carr_1 = MCl$ $MCa = 1.3571$ $MCl = 1.4463$

$Cmin = \min(Carr)$ $Cmax = \max(Carr)$

$Cmin = 1.3571$ $Cmax = 1.4463$ $frat = \frac{Cmin}{Cmax}$ $frat = 0.9383$

$Tlo = Tli + \frac{Qlm}{MCl}$ $Tai = Tao + \frac{Qlm}{MCa}$ $Taa = 0.5 \cdot (Tao + Tai)$

Prop. Gly. out & in temps.: $Tlo = 20.2972$ $Tli = 27.1053$

Air out & in Temps: $Tao = 25$ $Tai = 17.7443$

Air average: $Taa = 21.3722$

$\Delta Tl = Tlo - Tli$ $\Delta Tl = 6.8081$

$\Delta Ta = Tai - Tao$ $\Delta Ta = 7.2557$

Effectiveness:

$\varepsilon a = \frac{MCa \cdot (Tai - Tao)}{Cmin \cdot (Tai - Tli)}$ $\varepsilon a = 0.7751$

$\varepsilon l = \frac{MCl \cdot (Tlo - Tli)}{Cmin \cdot (Tai - Tli)}$ $\varepsilon l = 0.7751$ (Check)

Log-mean temperature difference:

$\Delta T1 = (Tai - Tlo)$ $\Delta T2 = (Tao - Tli)$

$\Delta T1 = 2.5529$

$\Delta T2 = 2.1053$

$\Delta Tlm = \frac{\Delta T1 - \Delta T2}{\ln\left(\frac{\Delta T1}{\Delta T2}\right)}$

$\Delta Tlm = 2.3219$

Required effective area x heat transfer coefficient:

$AU = \frac{Emax}{\Delta Tlm}$ $AU = 2.1091$ kW/deg. C

Counterflow Heat Exchanger Solution Summary (S.I. units):

	Area x Heat Transfer Coeff:	AU = 2.1091	kW/deg. C (effective)
	Required Effectiveness:	εa = 0.7751	
	Max. Medium flowrate:	Φlm = 28.8671	kg/min
	Design Air flowrate:	Φa = 1.3504	kg/s
	Fan air flowrate:	Voa = 0.9645	cubic m/s
70% Propylene Glycol —>	Liquid inlet temperature:	Tli = -27.1053	deg. C
	Liquid outlet temperature:	Tlo = -20.2972	deg. C
	Out-In temp. diff.	ΔTl = 6.8081	Celsius deg.
	Air inlet temperature:	Tai = -17.7443	deg. C
	Air outlet temperature:	Tao = -25	deg. C
	In-Out temp. diff.	ΔTa = 7.2557	Celsius deg.
	Average air temperature:	Taa = -21.3722	deg. C

Imperial conversions:

$AUe = hcf \cdot \frac{AU}{tcf}$

$Tlie = tcf \cdot Tli - 32.0$ $\quad Tloe = tcf \cdot Tlo - 32.0$

$Taie = tcf \cdot Tai - 32.0$ $\quad Taoe = tcf \cdot Tao - 32.0$ $\quad Taae = tcf \cdot Taa - 32.0$

$Φle = wcf \cdot Φl \cdot 60.$ $\quad Φae = wcf \cdot Φa \cdot 60.$ $\quad Voae = lcf^3 \cdot Voa \cdot 60.$

Counterflow Heat Exchanger Solution Summary (Imperial units):

Area x Heat Transfer Coeff:	AUe = 3997.992	Btu/h deg. F (effective)
Required Effectiveness:	εa = 0.7751	
Max. Medium flowrate:	Φle = 63.6411	lb/min
Design Air flowrate:	Φae = 178.6215	lb/min
Fan air flowrate:	Voae = 2043.67	cfm
Liquid inlet temperature:	Tlie = -16.7896	deg. F
Liquid outlet temperature:	Tloe = -4.5349	deg. F
Air inlet temperature:	Taie = 0.0603	deg. F
Air outlet temperature:	Taoe = -13	deg. F
Average air temperature:	Taae = -6.4699	deg. F

Solution Check:

$\Delta Tl = Tlo - Tli$ $\Delta Ta = Tao - Tai$

$\Delta Tl = 6.8081$ $\Delta Ta = -7.2557$

$RETa = \Phi a \cdot Ca \cdot \Delta Ta$ Rate of Energy Transfer: $RETa = -9.8468$ kW

$RETl = \Phi l \cdot Cp_l \cdot \Delta Tl$ Rate of Energy Transfer: $RETl = 9.8468$ kW

Design Notes: (1) Exchanger specification based on initial (max.) refrigeration load but minimum design temperature difference (following initial phase).

(2) Independent design variables are shown above in italics & are underlined.

APPENDIX II

COMPUTER MODELS USED TO PREDICT

BACTERIAL GROWTH ON MEAT SURFACES

Time-temperature Integration to predict growth of *Salmonella typhimurium*

Prediction of growth rates between 15 an 7 Celsius:

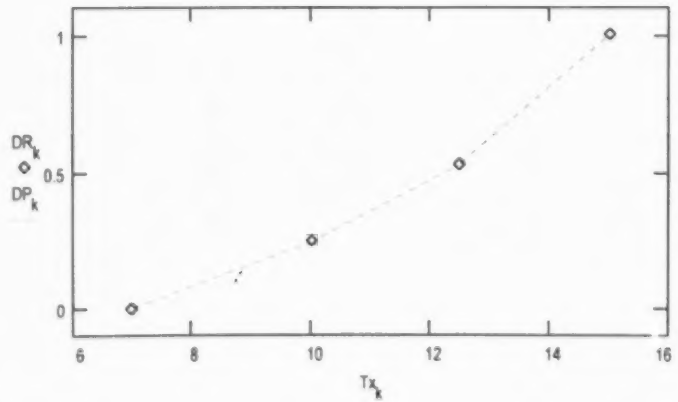
$Tx_0 := 7.0$ $D7 := 0.0$

$Tx_1 := 10.0$ $D10 := 0.0719$ $k := 0..3$

$Tx_2 := 12.5$ $D12 := 0.1538$

$Tx_3 := 15.0$ $D15 := 0.2941$ $DR_0 := 0$ $DR_1 := \frac{D10}{D15}$ $DR_2 := \frac{D12}{D15}$ $DR_3 := 1$

$$F(x) := \begin{bmatrix} 1 \\ x \\ x^6 \end{bmatrix} \qquad C := \text{linfit}(Tx, DR, F) \qquad C = \begin{bmatrix} 0.4827 \\ 0.0684 \\ 4.0006 \cdot 10^{-8} \end{bmatrix} \qquad DP_k := C \cdot F(Tx_k)$$



$DP_3 = 0.9995$

$DP_0 = 0.001$

$A := \text{READPRN}(\text{bkdeep\_t})$ $SE := 0.6275$ $\text{GENTIME}(T,d,e,f) := d + e\cdot\exp(-f\cdot T)$

$\theta := A^{\langle 0 \rangle}$ $N := \text{last}(\theta)$ $N = 252$ $j := 0..N$ $k := 1..N$ $\Delta\theta := \frac{\max(\theta)}{N}$ $\Delta\theta\cdot 60 = 5$ minutes

$Ts := A^{\langle 2 \rangle}$ $Tsp_j := Ts_j + SE$ $Tsm_j := Ts_j - SE$ $Tng := 15.0$

1. <u>Growth on Fatty tissue:</u> $df := 0.257$ $ef := 5.104$ $ff := 0.092$ $\Theta 15 := \text{GENTIME}(15,df,ef,ff)$

$\Theta_j := \text{GENTIME}(Ts_j,df,ef,ff)$ $\Theta p_j := \text{GENTIME}(Tsp_j,df,ef,ff)$ $\Theta m_j := \text{GENTIME}(Tsm_j,df,ef,ff)$

$D_j := \text{if}[Ts_j > Tng, (\Theta_j)^{-1}, 0]$ $Dp_j := \text{if}[Tsp_j > Tng, (\Theta p_j)^{-1}, 0]$ $Dm_j := \text{if}[Tsm_j > Tng, (\Theta m_j)^{-1}, 0]$

$D_j := \text{if}[(Ts_j \le 15)\cdot(Ts_j > 7), \Theta 15^{-1}\cdot C\cdot F(Ts_j), D_j]$ $Dp_j := \text{if}[(Tsp_j \le 15)\cdot(Tsp_j > 7), \Theta 15^{-1}\cdot C\cdot F(Tsp_j), Dp_j]$ $Dm_j := \text{if}[(Tsm_j \le 15)\cdot(Tsm_j > 7), \Theta 15^{-1}\cdot C\cdot F(Tsm_j), Dm_j]$

$G_0 := 0$ $Gp_0 := 0$ $Gm_0 := 0$

$G_k := G_{k-1} + 0.5\cdot(D_{k-1} + D_k)\cdot\Delta\theta$ $Gp_k := Gp_{k-1} + 0.5\cdot(Dp_{k-1} + Dp_k)\cdot\Delta\theta$ $Gm_k := Gm_{k-1} + 0.5\cdot(Dm_{k-1} + Dm_k)\cdot\Delta\theta$

$GT := G_N$ $P := 2^{GT}\cdot 100$ $GpT := Gp_N$ $Pp := 2^{GpT}\cdot 100$ $GmT := Gm_N$ $Pm := 2^{GmT}\cdot 100$

$GT = 1.0588$ $P = 208.32$ $GpT = 1.2935$ $Pp = 245.12$ $GmT = 0.8524$ $Pm = 180.55$

$Gsep := GpT - GT$ $Gsep = 0.2347$ $Psep := Pp - P$ $Psep = 36.8014$

$Gsem := GT - GmT$ $Gsem = 0.2064$ $Psem := P - Pm$ $Psem = 27.7679$

Process: CON **1. Fatty Tissue**

No. of generations: GT = 1.0588

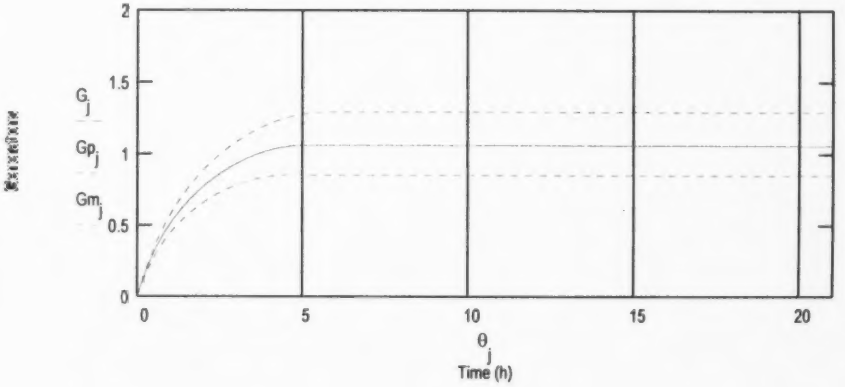
Stnd. Error (high): Gsep = 0.2347

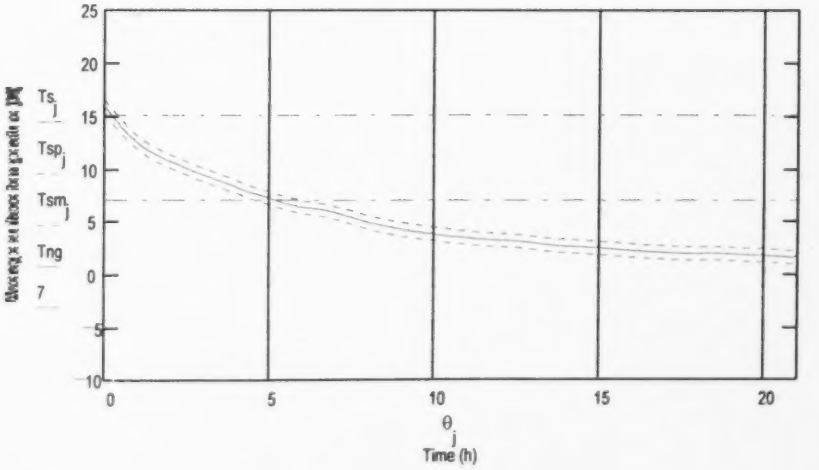
Stnd. Error (low): Gsem = 0.2064

Pop. increase (%): P = 208.32

Stnd. Error (high): Psep = 36.8014

Stnd. Error (low): Psem = 27.7679





Tng = 15 Celsius

2. Growth on Lean tissue: $dl = 0.188$ $el = 7.65$ $fl = 0.09$ $\Theta 15 = GENTIME(15, dl, el, fl)$

$\Theta_j = GENTIME(Ts_j, dl, el, fl)$

$D_j = if(Ts_j > Tng, (\Theta_j)^{-1}, 0)$

$D_j = if((Ts_j \le 15) \cdot (Ts_j > 7), \Theta 15^{-1} \cdot C \cdot F(Ts_j), D_j)$

$G_0 = 0$

$G_k = G_{k-1} + 0.5 \cdot (D_{k-1} + D_k) \cdot \Delta\theta$

$GT = G_N$ $P = 2^{GT} \cdot 100$

$GT = 0.7518$ $P = 168.39$

$\Theta p_j = GENTIME(Tsp_j, dl, el, fl)$

$Dp_j = if(Tsp_j > Tng, (\Theta p_j)^{-1}, 0)$

$Dp_j = if((Tsp_j \le 15) \cdot (Tsp_j > 7), \Theta 15^{-1} \cdot C \cdot F(Tsp_j), Dp_j)$

$Gp_0 = 0$

$Gp_k = Gp_{k-1} + 0.5 \cdot (Dp_{k-1} + Dp_k) \cdot \Delta\theta$

$GpT = Gp_N$ $Pp = 2^{GpT} \cdot 100$

$GpT = 0.919$ $Pp = 189.08$

$\Theta m_j = GENTIME(Tsm_j, dl, el, fl)$

$Dm_j = if(Tsm_j > Tng, (\Theta m_j)^{-1}, 0)$

$Dm_j = if((Tsm_j \le 15) \cdot (Tsm_j > 7), \Theta 15^{-1} \cdot C \cdot F(Tsm_j), Dm_j)$

$Gm_0 = 0$

$Gm_k = Gm_{k-1} + 0.5 \cdot (Dm_{k-1} + Dm_k) \cdot \Delta\theta$

$GmT = Gm_N$ $Pm = 2^{GmT} \cdot 100$

$GmT = 0.6051$ $Pm = 180.55$

$Gsep = GpT - GT$ $Gsep = 0.1672$

$Gsem = GT - GmT$ $Gsem = 0.1467$

$Psep = Pp - P$ $Psep = 20.687$

$Psem = P - Pm$ $Psem = 12.1633$

Process: CON **2. Lean Tissue**

No. of generations: GT = 0.7518

Stnd. Error (high): Gsep = 0.1672

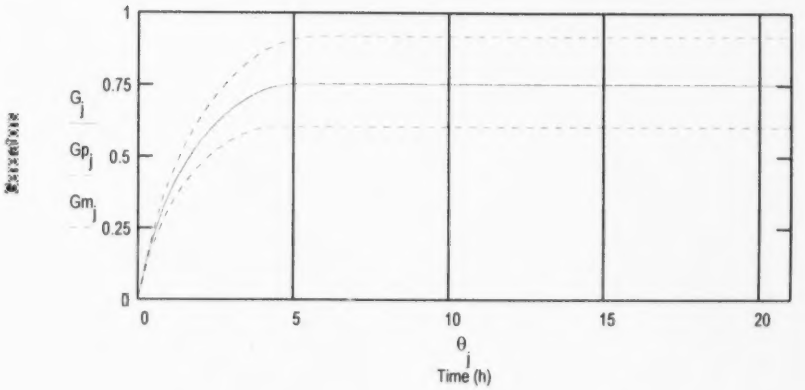
Stnd. Error (low): Gsem = 0.1467

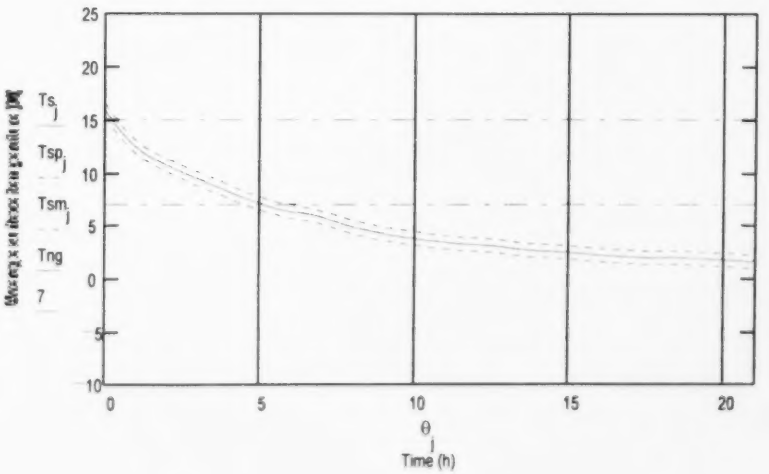
Pop. increase (%): P = 168.39

Stnd. Error (high): Psep = 20.687

Stnd. Error (low): Psem = 12.1633

Tng = 15 Celsius





Time-temperature Integration to determine theoretical growth of E-coli

$A := \text{READPRN}(b3deep\_t)$ $SE := 0.6100$ $GF1(T) := (0.0513 \cdot T - 0.17)^2$ $GF2(T) := (0.027 \cdot T - 0.55)^2$

$\theta := A^{<0>}$ $N := \text{last}(\theta)$ $N = 252$ $j := 0..N$ $k := 1..N$ $\Delta\theta := \frac{\max(\theta)}{N}$ $\Delta\theta \cdot 60 = 5$ minutes

$Ts := A^{<2>}$ $\max(Ts) = 22.95$ $Tsp_j := Ts_j + SE$ $\max(Tsp) = 23.56$ $Tsm_j := Ts_j - SE$ $\max(Tsm) = 22.34$

$V_j := 0.0$ $Vp_j := 0.0$ $Vm_j := 0.0$

$V_j := \text{if}(Ts_j > 7.0) \cdot (Ts_j < 30), GF1(Ts_j), V_j)$ $Vp_j := \text{if}(Tsp_j > 7.0) \cdot (Tsp_j < 30), GF1(Tsp_j), Vp_j)$ $Vm_j := \text{if}(Tsm_j > 7.0) \cdot (Tsm_j < 30), GF1(Tsm_j), Vm_j)$

$V_j := \text{if}(Ts_j > 30) \cdot (Ts_j < 40), GF2(Ts_j), V_j)$ $Vp_j := \text{if}(Tsp_j > 30) \cdot (Tsp_j < 40), GF2(Tsp_j), Vp_j)$ $Vm_j := \text{if}(Tsm_j > 30) \cdot (Tsm_j < 40), GF2(Tsm_j), Vm_j)$

$V_j := \text{if}(Ts_j > 40) \cdot (Ts_j < 47), 2.66, V_j)$ $Vp_j := \text{if}(Tsp_j > 40) \cdot (Tsp_j < 47), 2.66, Vp_j)$ $Vm_j := \text{if}(Tsm_j > 40) \cdot (Tsm_j < 47), 2.66, Vm_j)$

$G_0 := 0$ $G_k := G_{k-1} + 0.5 \cdot (V_{k-1} + V_k) \cdot \Delta\theta$ $Gp_0 := 0$ $Gp_k := Gp_{k-1} + 0.5 \cdot (Vp_{k-1} + Vp_k) \cdot \Delta\theta$ $Gm_0 := 0$ $Gm_k := Gm_{k-1} + 0.5 \cdot (Vm_{k-1} + Vm_k) \cdot \Delta\theta$

$GT := G_N$ $P := 2^{GT} \cdot 100$ $GpT := Gp_N$ $Pp := 2^{GpT} \cdot 100$ $GmT := Gm_N$ $Pm := 2^{GmT} \cdot 100$

$GT = 0.7344$ $P = 166.37$ $GpT = 0.8156$ $Pp = 176$ $GmT = 0.6598$ $Pm = 157.98$

$Gsep := GpT - GT$ $Gsep = 0.0812$ $Psep := Pp - P$ $Psep = 9.6316$

$Gsem := GT - GmT$ $Gsem = 0.0747$ $Psem := P - Pm$ $Psem = 8.3915$

Process: PC3

No. of generations: GT = 0.7344

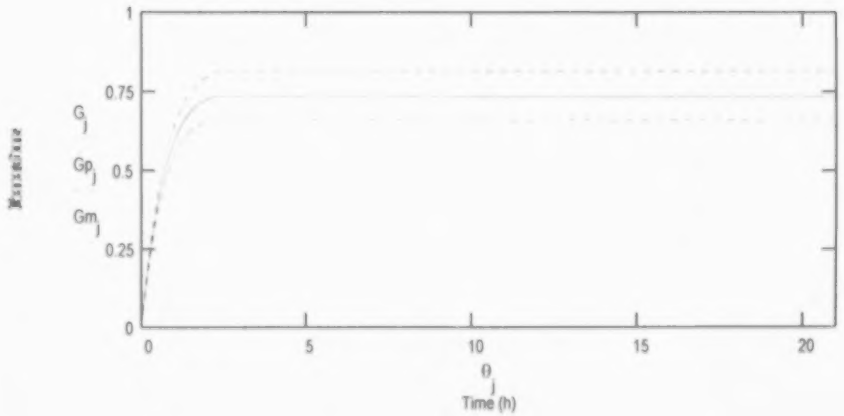
Stnd. Error (high): Gsep = 0.0812

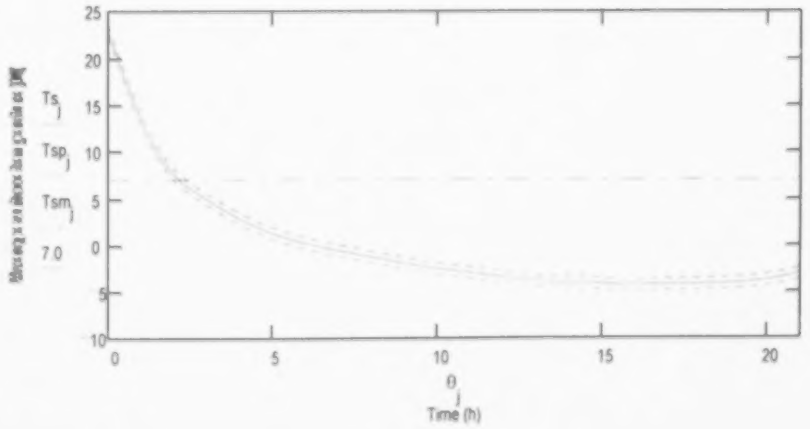
Stnd. Error (low): Gsem = 0.0747

Pop. increase (%): P = 166.37

Stnd. Error (high): Psep = 9.6316

Stnd. Error (low): Psem = 8.3915





Time-temperature Integration to determine theoretical growth of Pseudomonads

$A := \text{READPRN}(\text{bkdeep\_1})$ $SE := 0.4375$ $GF1(T) := (0.033 \cdot T - 0.27)^2$

$\theta := A^{\langle 0 \rangle}$ $N := \text{last}(\theta)$ $N = 252$ $j := 0..N$ $k := 1..N$ $\Delta\theta := \frac{\max(\theta)}{N}$ $\Delta\theta \cdot 60 = 5$ minutes

$Ts := A^{\langle 2 \rangle}$

$Tsp_j := Ts_j + SE$

$Tsm_j := Ts_j - SE$

$V_j := GF1(Ts_j)$

$Vp_j := GF1(Tsp_j)$

$Vm_j := GF1(Tsm_j)$

$V_j := \text{if}(Ts_j < 2.0, 0.0, V_j)$

$Vp_j := \text{if}(Tsp_j < 2.0, 0.0, Vp_j)$

$Vm_j := \text{if}(Tsm_j < 2.0, 0.0, Vm_j)$

$V_j := \text{if}[(Ts_j \geq 2.0) \cdot (Ts_j < 25), GF1(Ts_j), V_j]$

$Vp_j := \text{if}[(Tsp_j \geq 2.0) \cdot (Tsp_j < 25), GF1(Tsp_j), Vp_j]$

$Vm_j := \text{if}[(Tsm_j \geq 2.0) \cdot (Tsm_j < 25), GF1(Tsm_j), Vm_j]$

$V_j := \text{if}[(Ts_j \geq 25) \cdot (Ts_j < 35), 1.0, V_j]$

$Vp_j := \text{if}[(Tsp_j \geq 25) \cdot (Tsp_j < 35), 1.0, Vp_j]$

$Vm_j := \text{if}[(Tsm_j \geq 25) \cdot (Tsm_j < 35), 1.0, Vm_j]$

$V_j := \text{if}(Ts_j \geq 35, 0.0, V_j)$

$Vp_j := \text{if}(Tsp_j \geq 35, 0.0, Vp_j)$

$Vm_j := \text{if}(Tsm_j \geq 35, 0.0, Vm_j)$

$G_0 := 0$ $G_k := G_{k-1} + 0.5 \cdot (V_{k-1} + V_k) \cdot \Delta\theta$

$Gp_0 := 0$ $Gp_k := Gp_{k-1} + 0.5 \cdot (Vp_{k-1} + Vp_k) \cdot \Delta\theta$

$Gm_0 := 0$ $Gm_k := Gm_{k-1} + 0.5 \cdot (Vm_{k-1} + Vm_k) \cdot \Delta\theta$

$GT := G_N$ $P := 2^{GT} \cdot 100$

$GpT := Gp_N$ $Pp := 2^{GpT} \cdot 100$

$GmT := Gm_N$ $Pm := 2^{GmT} \cdot 100$

$GT = 4.2729$ $P = 1933.22$

$GpT = 4.5419$ $Pp = 2329.36$

$GmT = 4.0128$ $Pm = 1614.22$

$Gsep := GpT - GT$ $Gsep = 0.2689$

$Gsem := GT - GmT$ $Gsem = 0.2602$

$Psep := Pp - P$ $Psep = 396.1413$

$Psem := P - Pm$ $Psem = 319.0062$

Process: CON

No. of generations: GT = 4.2729

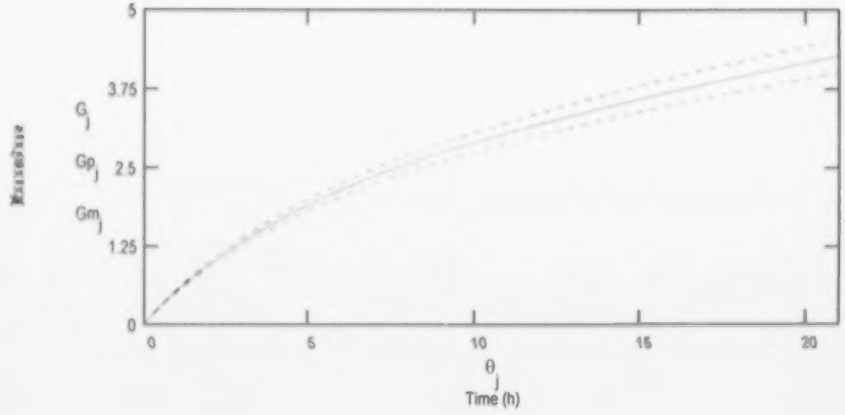
Stnd. Error (high): Gsep = 0.2689

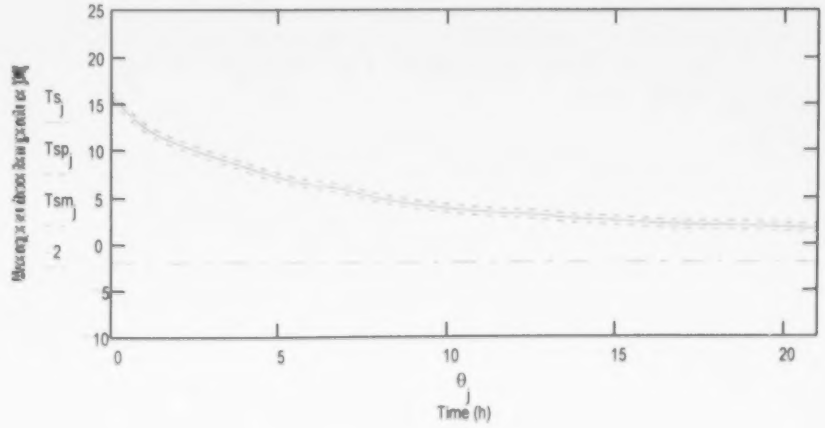
Stnd. Error (low): Gsem = 0.2602

Pop. increase (%): P = 1933.22

Stnd. Error (high): Psep = 396.1413

Stnd. Error (low): Psem = 319.0062





APPENDIX III

MATHEMATICAL MODELS OF THE PSCHROMETRIC AND PHYSICAL PROPERTIES OF AIR

Summary of Models used for Psychrometric and Physical Properties of Air

PROPERTY	FORMULA †	UNITS	SOURCE ‡
Conductivity	$k = (24.13025 + 0.079498 \bullet T_c - 0.000032 \bullet T_c^2) \bullet 10^{-3}$	$W\ m^{-1}\ K^{-1}$	1
Density (dry)	$\rho = 1.293298 - 0.00477 \bullet T_c + 0.000017 \bullet T_c^2$	$kg\ m^{-3}$	1
Humidity ratio	$H = 0.622 \bullet (P_v/(P_A - P_v))$	-	2
Humid Volume	$V = (2.83 + 4.56 \bullet H) \bullet (273.16 + T_c) \bullet 10^{-3}$	$m^3\ kg^{-1}$	2
Mass Diffusivity ♣	$\alpha = (0.218435 + 0.001502 \bullet T_c - 3.6007 \bullet 10^{-7} \bullet T_c^2) \bullet 10^{-4}$	$m^2\ s^{-1}$	1
Prandtl No.	$Pr = 0.714981 - 0.000299 \bullet T_c + 6.060606 \bullet 10^{-7} \bullet T_c^2$	-	1
Vapour Pressure	$P_v = e^{(16.654 - 4030.2/(T_c + 235.0))}$	Pa	3
Viscosity	$\mu = (17.160884 + 0.049503 \bullet T_c - 0.000047 \bullet T_c^2) \bullet 10^{-6}$	$kg\ m^{-1}\ s^{-1}$	1
Specific Heat	$C_p = 1.005619 + 0.000029 \bullet T_c$	$kJ\ kg^{-1}\ K^{-1}$	1

† T_c denotes Temperature (°C). P_v denotes vapour pressure (Pa). P_A denotes atmospheric pressure (Pa)
All formulas acceptable for $-20°C < T_c < 20°C$ and developed by regression analysis from published data.

‡ Data sources: (1) Bolz and Tuve, 1976; (2) Geankoplis, 1983; (3) Antoine Equation.

♣ Diffusivity of water vapour in air.

APPENDIX IV

ANALYTICAL COMPUTER PROGRAM

TO ESTIMATE EXPERIMENTAL PARAMETERS

IN MODEL OF EVAPORATION RATE FROM BEEF CARCASSES

Moisture Loss Prediction

Process: PC1

Note: Enter liveweight, trimmed Wt., & change output filename!

Number of experimental (time) values: $N := 241$ $j := 0..N-1$ $\theta_j := j \cdot 5$ $\theta s_j := (\theta_j)^2$

Regression smoothing radius: $p := 15$ $p1 := p+1$ $jp := 1..N-1$

$\theta max := max(\theta)$ $\Delta\theta := \frac{\theta_{N-1} - \theta_0}{N-1}$

$F := READPRN(b3deep\_t)$ $k := 1..N-1$

$\theta max = 1200$

Mean Live Wt. $Wl := 511.92$ Surface Temp. $Ts := F^{<2>}$

$\Theta_j := \frac{\theta_j}{60}$ $\Delta\theta = 5$

Mean Trimmed Wt. $Ws := 150.92$ Air Temp. $Ta := F^{<5>}$

$\Theta max := max(\Theta)$

Film temperature: $Tf_j := (Ta_j + Ts_j) \cdot 0.5$

$\Theta max = 20$

Air Property Models (see air_prop.tc file for regressions):

Atmospheric pressure: $Pa := 101.32$

$DENA(TC) := 1.293298 - 0.00477 \cdot TC + 0.000017 \cdot TC^2$

$SPECA(TC) := 1.005619 + 0.000029 \cdot TC$

$VISCA(TC) := (17.160884 + 0.049503 \cdot TC - 0.000047 \cdot TC^2) \cdot 10^{-6}$

$HUMA(Pv) := 0.622 \cdot \left[\frac{Pv}{(Pa - Pv)}\right]$

$CONDA(TC) := (24.13025 + 0.079498 \cdot TC - 0.000032 \cdot TC^2) \cdot 10^{-3}$

$PRNDTLA(TC) := 0.714981 - 0.000299 \cdot TC + 6.060606 \cdot 10^{-7} \cdot TC^2$

$PRESSV(TC) := \exp\left[16.654 - \frac{4030.2}{(TC + 235.0)}\right]$ Antoine Eq'n

$HUMVOL(H, TC) := (2.83 + 4.56 \cdot H) \cdot (273.16 + TC) \cdot 10^{-3}$

$DIFFAW(TC) := (0.218435 + 0.001502 \cdot TC - 3.6007 \cdot 10^{-7} \cdot TC^2) \cdot 10^{-4}$

Estimate of Beef Side Surface Area and Equivalent Slab

Experimental exponent: $\gamma := 0.077502521$ Trim factor: $ft := 0.85$

Ratio of internal / external surface areas: $fr := 0.73167$

Live animal surface area (m^2): $Al := \gamma \cdot Wl^{\frac{2}{3}}$ $Al = 4.96$

Estimated Side area (m^2): $As := \frac{(1 + fr) \cdot ft \cdot Al}{2}$ $As = 3.65$

Avg. beef side density (kg/m^3) $\rho s := 996.0$

Ratio side width / length: $Rw := 0.2509$

Volume of beef side (m^3) $Vs := \frac{Ws}{\rho s}$

Ratio "$\sqrt{2}/2\ A^{3}$": $Rva := \frac{Vs^2}{As^3}$ $Rva \cdot 10^4 = 4.721294$

Guess: $Rx := 0.06$

Given

$$Rva = \frac{(Rx \cdot Rw)^2}{8 \cdot (Rx \cdot Rw + Rw + Rx)^3}$$

$Rx > 0$ $Rx < 0.5$

$Rd := FIND(Rx)$

$cmf := 0.3048^{-1}$

Ratio side depth / length = $Rd = 0.04059$ $Dl := \left(\frac{0.5 \cdot As}{Rd \cdot Rw + Rd + Rw}\right)^{\frac{1}{2}}$ $Dw := Rw \cdot Dl$ $Dd := Rd \cdot Dl$

Slab in Feet:

Equivalent side length (m) = $Dl = 2.4596$ length $Dl \cdot cmf = 8.07$

Equivalent side width (m) = $Dw = 0.6171$ width $Dw \cdot cmf = 2.025$

Equivalent side depth (m) = $Dd = 0.0998$ depth $Dd \cdot cmf = 0.328$

Air Properties:

Significant length: $Ds := Dl$ Air velocity reduction factor: $far := 0.10$

Reduced velocity: $V_j := far \cdot 4.0415$ $\max(V) = 0.40415$ $\min(V) = 0.40415$

Reynolds Number: $RE_j := \frac{Ds \cdot V_j \cdot DENA(Tf_j)}{VISCA(Tf_j)}$ $\max(RE) = 7.83 \cdot 10^4$ $\min(RE) = 6.594 \cdot 10^4$ $\text{mean}(RE) = 7.661 \cdot 10^4$

Mass Diffusivity: $Daw_j := DIFFAW(Tf_j)$ $\max(Daw) = 2.487 \cdot 10^{-5}$ $\min(Daw) = 2.084 \cdot 10^{-5}$

Thermal Diffusivity: $Dt_j := \frac{CONDA(Tf_j)}{DENA(Tf_j) \cdot SPECA(Tf_j)}$ $\max(Dt) = 0.021$ $\min(Dt) = 0.018$

Prandtl Number: $Pr_j := PRNDTLA(Tf_j)$ $\max(Pr) = 0.717$ $\min(Pr) = 0.709$

Air Moisture Concentrations

Surface $Pvs_j := PRESSV(Ts_j)$ Air $Pva_j := PRESSV(Ta_j)$

$Hvs_j := HUMA(Pvs_j)$ $Cs_j := \frac{Hvs_j}{HUMVOL(Hvs_j, Ts_j)}$ $Hva_j := HUMA(Pva_j)$ $Ca_j := \frac{Hva_j}{HUMVOL(Hva_j, Ta_j)}$

Predicted evaporation rate:

$\alpha := 0.5$ $\beta := 0.105$ Rate coeff. $\kappa_j := \frac{(Dt_j)^{\frac{1}{3}} \cdot (Daw_j)^{\frac{2}{3}} \cdot (Pr_j)^{\frac{1}{3}}}{Ds} \cdot 60$ m/min

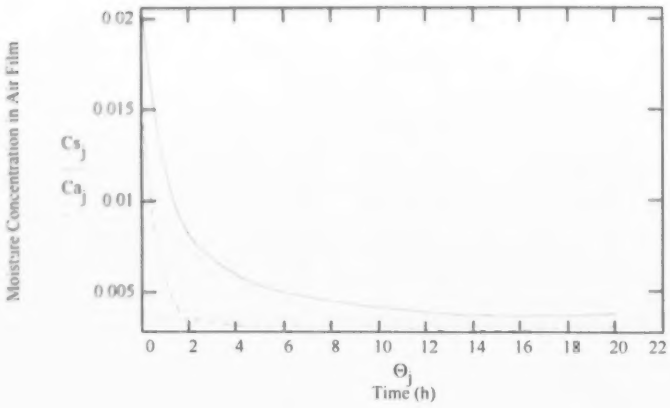
Concentration difference: $\Delta C_j := Cs_j - Ca_j$

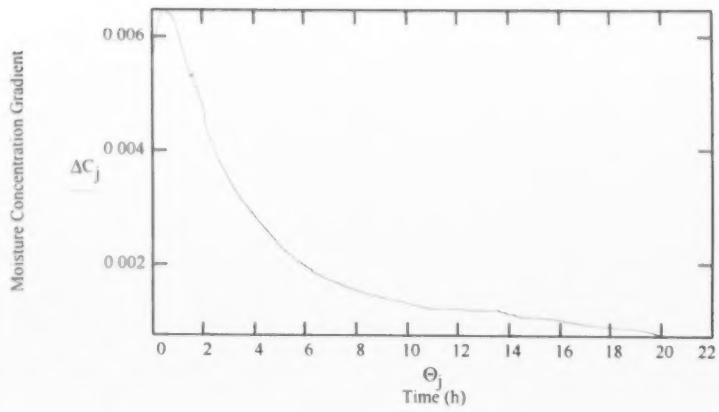
Predicted evaporation rate: $EP_j := \kappa_j \cdot As \cdot \beta \cdot (RE_j)^{\alpha} \cdot \Delta C_j$ $\text{mean}(EP) = 9.467 \cdot 10^{-4}$

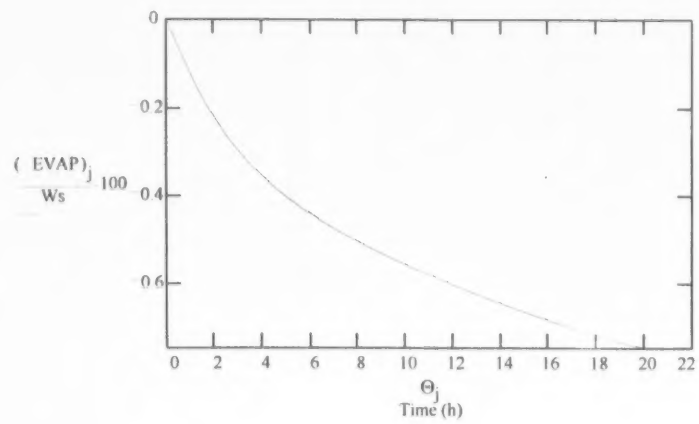
$EVAP_0 := 0$ $EVAP_k := EVAP_{k-1} + \frac{(EP_{k-1} + EP_k) \cdot \Delta\theta}{2}$

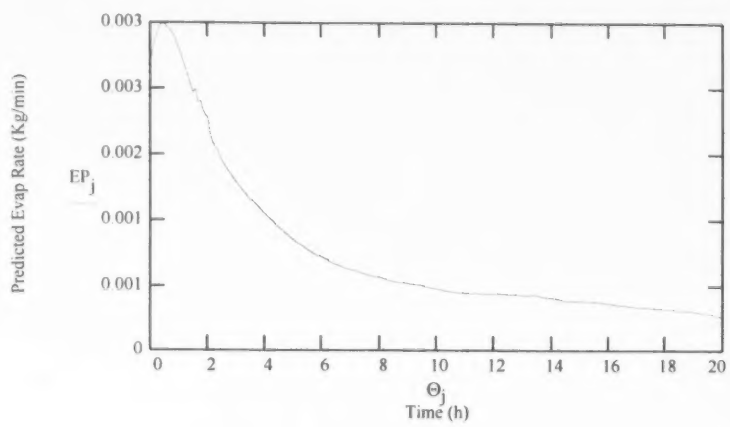
Predicted total moisture loss: $ML := EVAP_{N-1}$ $ML = 1.133$ $ML\% := \frac{ML}{Ws} \cdot 100$ $ML\% = 0.751$

Max. Evaporation rate: $\max(EP) \cdot 10^3 = 3.2$ grams per minute


Moisture Concentration in Air Film
0.02
0.015
Cs_j
Ca_j
0.01
0.005
0 2 4 6 8 10 12 14 16 18 20 22
Θ_j
Time (h)


Moisture Concentration Gradient
0.006
0.004
ΔC_j
0.002
0 2 4 6 8 10 12 14 16 18 20 22
Θ_j
Time (h)


(EVAP)_j / Ws 100
0
0.2
0.4
0.6
0 2 4 6 8 10 12 14 16 18 20 22
Θ_j
Time (h)


Predicted Evap Rate (Kg/min)
0.003
0.003
0.002
EP_j
0.001
0.001
0
0 2 4 6 8 10 12 14 16 18 20
Θ_j
Time (h)

APPENDIX V

EXAMPLE COMPUTER PROGRAM USED TO MERGE AND ORGANIZE

PROCESS DATA SETS FOR SUBSEQUENT ANALYSES

WITH EXAMPLE PROCESS DATA FILE (ONE RUN)

Averaging & Plotting of Carcass Temperature Profiles

Left - RC3

F1 := READPRN(sep07) F3 := READPRN(aug17) F5 := READPRN(jul26)

F2 := READPRN(aug26) F4 := READPRN(aug03) F6 := READPRN(sep16)

Number of data values in each array: N := last($F1^{\langle 0 \rangle}$) N = 252 j := 0..N

Number of runs to average (2-6): nr := 6 i := 0..nr - 1

Variable to be plotted: Loin SurfaceTemperature

Data column of variable (0-24): nt := 3

Time arrays:

$\theta_j := j \cdot 5$ $H_j := \frac{\theta_j}{60}$

$\theta s_j := (\theta_j)^2$ θmax := max(θ)

θmax = 1260

Scaling function: $UNO(x, mn, mx) := \frac{x_j - mn}{mx - mn}$

T1 := $F1^{\langle nt \rangle}$	mn1 := min(T1)	mx1 := max(T1)	$U1_j$:= UNO(T1, mn1, mx1)
T2 := $F2^{\langle nt \rangle}$	mn2 := min(T2)	mx2 := max(T2)	$U2_j$:= UNO(T2, mn2, mx2)
T3 := $F3^{\langle nt \rangle}$	mn3 := min(T3)	mx3 := max(T3)	$U3_j$:= UNO(T3, mn3, mx3)
T4 := $F4^{\langle nt \rangle}$	mn4 := min(T4)	mx4 := max(T4)	$U4_j$:= UNO(T4, mn4, mx4)
T5 := $F5^{\langle nt \rangle}$	mn5 := min(T5)	mx5 := max(T5)	$U5_j$:= UNO(T5, mn5, mx5)
T6 := $F6^{\langle nt \rangle}$	mn6 := min(T6)	mx6 := max(T6)	$U6_j$:= UNO(T6, mn6, mx6)

Out Matrix One:

$M1_{j,0} := T1_j$

$M1_{j,1} := T2_j$

$M1_{j,2} := T3_j$

$M1_{j,3} := T4_j$

$M1_{j,4} := T5_j$

$M1_{j,5} := T6_j$

Out Matrix Two:

$M2_{j,0} := U1_j$

$M2_{j,1} := U2_j$

$M2_{j,2} := U3_j$

$M2_{j,3} := U4_j$

$M2_{j,4} := U5_j$

$M2_{j,5} := U6_j$

Threshold temperatures:

Ta := 10 Tb := 0

Search Function:

$JF(TA, Tt) := if(TA_j > Tt, j, 0)$

Interpolation Function:

$\Theta F(\theta m, \theta p, Tm, Tp, Ta) := \theta m + \frac{(Ta - Tm + 0.0001) \cdot (\theta p - \theta m)}{(Tp - Tm + 0.0001)}$

Time to reach threshold temperature: $Ta = 10$

$J1_j := JF(T1, Ta)$

$j1m := max(J1)$ $\theta_{j1m} = 80$

$\theta a_0 := \Theta F(\theta_{j1m}, \theta_{j1m+1}, T1_{j1m}, T1_{j1m+1}, Ta)$

$\theta a_0 = 85$

$J2_j := JF(T2, Ta)$

$j2m := max(J2)$ $\theta_{j2m} = 110$

$\theta a_1 := \Theta F(\theta_{j2m}, \theta_{j2m+1}, T2_{j2m}, T2_{j2m+1}, Ta)$

$\theta a_1 = 112.499$

$J3_j := JF(T3, Ta)$

$j3m := max(J3)$ $\theta_{j3m} = 95$

$\theta a_2 := \Theta F(\theta_{j3m}, \theta_{j3m+1}, T3_{j3m}, T3_{j3m+1}, Ta)$

$\theta a_2 = 100$

$J4_j := JF(T4, Ta)$

$j4m := max(J4)$ $\theta_{j4m} = 120$

$\theta a_3 := \Theta F(\theta_{j4m}, \theta_{j4m+1}, T4_{j4m}, T4_{j4m+1}, Ta)$

$\theta a_3 = 122.499$

$J5_j := JF(T5, Ta)$

$j5m := max(J5)$ $\theta_{j5m} = 95$

$\theta a_4 := \Theta F(\theta_{j5m}, \theta_{j5m+1}, T5_{j5m}, T5_{j5m+1}, Ta)$

$\theta a_4 = 100$

$J6_j := JF(T6, Ta)$

$j6m := max(J6)$ $\theta_{j6m} = 90$

$\theta a_5 := \Theta F(\theta_{j6m}, \theta_{j6m+1}, T6_{j6m}, T6_{j6m+1}, Ta)$

$\theta a_5 = 93.75$

$$\theta aav := \left(\frac{1}{nr}\right) \cdot \sum_{i=0}^{nr-1} \theta a_i \qquad \theta avar := \left(\frac{1}{nr-1}\right) \cdot \sum_{i=0}^{nr-1} (\theta a_i - \theta aav)^2 \qquad \theta asd := \sqrt{\theta avar} \qquad \theta ase := \sqrt{\frac{\theta avar}{nr}}$$

$Haav := \frac{\theta aav}{60}$ $\theta aav = 102.291$ min. $\theta avar = 179.005$ $Hase := \frac{\theta ase}{60}$ $\theta ase = 5.462$ min.

$Haav = 1.705$ h. $\theta asd = 13.379$ $Hase = 0.091$ h.

Time to reach low threshold temperature: $Tb = 0$ $Nm = N - 1$

$J1_j = JF(T1, Tb)$ $j1m = \max(J1)$ $J2_j = JF(T2, Tb)$ $j2m = \max(J2)$ $J3_j = JF(T3, Tb)$ $j3m = \max(J3)$

$j1m = if(j1m \geq Nm, Nm, j1m)$ $j2m = if(j2m \geq Nm, Nm, j2m)$ $j3m = if(j3m \geq Nm, Nm, j3m)$

$\theta b_0 = \Theta F(\theta_{j1m}, \theta_{j1m+1}, T1_{j1m}, T1_{j1m+1}, Tb)$ $\theta b_1 = \Theta F(\theta_{j2m}, \theta_{j2m+1}, T2_{j2m}, T2_{j2m+1}, Tb)$ $\theta b_2 = \Theta F(\theta_{j3m}, \theta_{j3m+1}, T3_{j3m}, T3_{j3m+1}, Tb)$

$\theta b_0 = if(j1m = Nm, \theta_{Nm}, \theta b_0)$ $\theta b_0 = 305$ $\theta b_1 = if(j2m = Nm, \theta_{Nm}, \theta b_1)$ $\theta b_1 = 360$ $\theta b_2 = if(j3m = Nm, \theta_{Nm}, \theta b_2)$ $\theta b_2 = 295$

$J4_j = JF(T4, Tb)$ $j4m = \max(J4)$ $J5_j = JF(T5, Tb)$ $j5m = \max(J5)$ $J6_j = JF(T6, Tb)$ $j6m = \max(J6)$

$j4m = if(j4m \geq Nm, Nm, j4m)$ $j5m = if(j5m \geq Nm, Nm, j5m)$ $j6m = if(j6m \geq Nm, Nm, j6m)$

$\theta b_3 = \Theta F(\theta_{j4m}, \theta_{j4m+1}, T4_{j4m}, T4_{j4m+1}, Tb)$ $\theta b_4 = \Theta F(\theta_{j5m}, \theta_{j5m+1}, T5_{j5m}, T5_{j5m+1}, Tb)$ $\theta b_5 = \Theta F(\theta_{j6m}, \theta_{j6m+1}, T6_{j6m}, T6_{j6m+1}, Tb)$

$\theta b_3 = if(j4m = Nm, \theta_{Nm}, \theta b_3)$ $\theta b_3 = 400$ $\theta b_4 = if(j5m = Nm, \theta_{Nm}, \theta b_4)$ $\theta b_4 = 270$ $\theta b_5 = if(j6m = Nm, \theta_{Nm}, \theta b_5)$ $\theta b_5 = 325$

$$\theta bav = \left(\frac{1}{nr}\right) \cdot \sum_{i=0}^{nr-1} \theta b_i \qquad \theta bvar = \left(\frac{1}{nr-1}\right) \cdot \sum_{i=0}^{nr-1} (\theta b_i - \theta bav)^2 \qquad \theta bsd = \sqrt{\theta bvar} \qquad \theta bse = \sqrt{\frac{\theta bvar}{nr}}$$

$Hbav = \frac{\theta bav}{60}$ $\theta bav = 325.833$ min. $\theta bvar = 2234.167$ $Hbse = \frac{\theta bse}{60}$ $\theta bse = 19.297$ min.

$Hbav = 5.431$ h. $\theta bsd = 47.267$ $Hbse = 0.322$ h.

$$AVG(z) := \frac{1}{nr} \cdot \sum_{i=0}^{nr-1} z_{j,i} \qquad VARE(z,x) := \left(\frac{1}{nr-1}\right) \cdot \sum_{i=0}^{nr-1} \left(z_{j,i} - x_j\right)^2 \qquad STERR(w) := \sqrt{\frac{w_j}{nr}}$$

$nr = 6$

Average & S.E. of raw data:

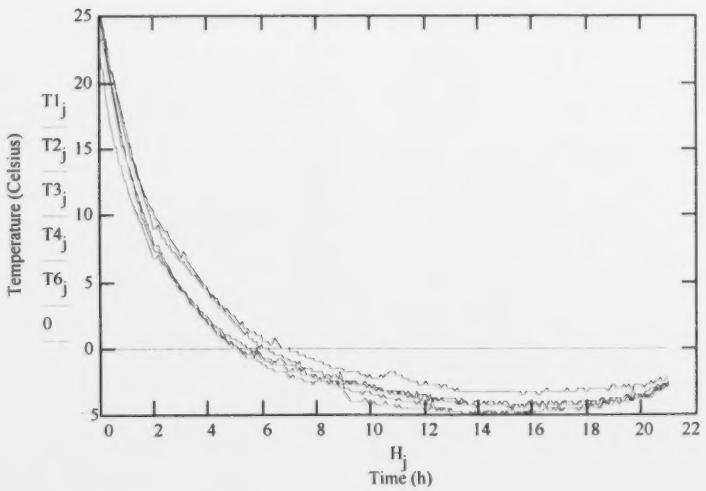
$Tav_j := AVG(M1)$ $\quad Tvar_j := VARE(M1, Tav)$ $\quad Tse_j := STERR(Tvar)$ $\quad Tse_j := if\left(|Tse_j| < 10^{-4}, 0, Tse_j\right)$

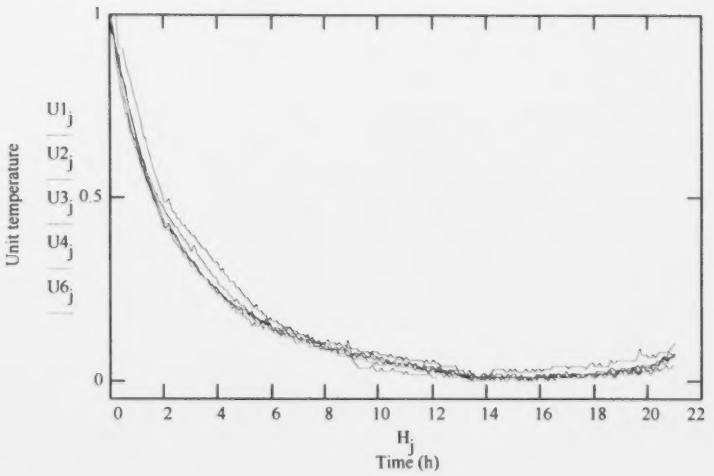
$MTvar := mean(Tvar)$ $\quad$ Stnd. error of mean temp. variance: $\quad SEMT := \sqrt{\frac{MTvar}{nr}}$ $\quad SEMT = 0.422$

Average & S.E. of scaled data:

$Uav_j := AVG(M2)$ $\quad Uvar_j := VARE(M2, Uav)$ $\quad Use_j := STERR(Uvar)$ $\quad Use_j := if\left(|Use_j| < 10^{-4}, 0, Use_j\right)$

$MUvar := mean(Uvar)$ $\quad$ Stnd. error of mean unit variance: $\quad SEMU := \sqrt{\frac{MUvar}{nr}}$ $\quad SEMU = 0.012$





Smoothing using N-point exponential decay model:

$p := 7$ $\quad p1 := p + 1$

Number of points in centre regression segments: $p + p1 = 15$ $\quad Tav_j := if(Tav_j = 0, 0.01, Tav_j)$

Low range: $lo := 0 .. p - 1$ $\quad NP_{lo} := p + lo$

Mid range: $k := p .. N - p1 + 1$ $\quad NP_k := p + p1$

High Range: $kh := N - p .. N$ $\quad NP_{kh} := p + N - kh - 1$

$$SUMLO(w) := \sum_{kc=0}^{lo+p-1} w_{kc} \qquad SUMMD(w) := \sum_{kc=k-p}^{k+p} w_{kc} \qquad SUMHI(w) := \sum_{kc=kh-p+1}^{N-1} w_{kc}$$

Log transformation Y: $TL_j := \ln(Tav_j + 10)$ $\quad$ Y*X Product: $TL\theta_j := TL_j \cdot \theta_j$

Sums:

$XS_{lo} := SUMLO(\theta)$ $\quad XSS_{lo} := SUMLO(\theta s)$ $\quad XS2_{lo} := (XS_{lo})^2$ $\quad YS_{lo} := SUMLO(TL)$ $\quad YXS_{lo} := SUMLO(TL\theta)$

$XS_k := SUMMD(\theta)$ $\quad XSS_k := SUMMD(\theta s)$ $\quad XS2_k := (XS_k)^2$ $\quad YS_k := SUMMD(TL)$ $\quad YXS_k := SUMMD(TL\theta)$

$XS_{kh} := SUMHI(\theta)$ $\quad XSS_{kh} := SUMHI(\theta s)$ $\quad XS2_{kh} := (XS_{kh})^2$ $\quad YS_{kh} := SUMHI(TL)$ $\quad YXS_{kh} := SUMHI(TL\theta)$

Coefficients: $B_j := \left(\frac{NP_j \cdot YXS_j - XS_j \cdot YS_j}{NP_j \cdot XSS_j - XS2_j}\right)$ $\quad AL_j := \left(\frac{1}{NP_j}\right) \cdot (YS_j - B_j \cdot XS_j)$ $\quad A_j := \exp(AL_j)$

Predicted curves: $Tsm_j := A_j \cdot \exp(B_j \cdot \theta_j) - 10$ $\quad DTsm_j := B_j \cdot A_j \cdot \exp(B_j \cdot \theta_j) \cdot 60$

$Tsm_j := if(|Tsm_j| < 10^{-4}, 0, Tsm_j)$

$Tsmx := \max(Tsm)$

$DTsm_j := if(|DTsm_j| < 10^{-4}, 0, DTsm_j)$

$Tsmn := \min(Tsm)$ $\quad Usm_j := UNO(Tsm, Tsmn, Tsmx)$

$Usm_j := if(|Usm_j| < 10^{-4}, 0, Usm_j)$

Numerical slope analysis:

$ll := 1..2$ $k := 3..N-3$ $lh := N-3..N$ $\Delta\theta := \theta_{100} - \theta_{99}$ $\Delta\theta = 5$

Forward difference (7 point) $DERfd(y) := \dfrac{(-29\cdot y_{ll-1} - 6\cdot y_{ll} + 9\cdot y_{ll+1} + 16\cdot y_{ll+2} + 15\cdot y_{ll+3} + 6\cdot y_{ll+4} - 11\cdot y_{ll+5})}{\Delta\theta\cdot 84}\cdot 60$

Central difference (7 point) $DERcd(y) := \dfrac{(y_{k+1} - y_{k-1} + 2\cdot y_{k+2} - 2\cdot y_{k-2} + 3\cdot y_{k+3} - 3\cdot y_{k-3})}{\Delta\theta\cdot 28}\cdot 60$ deg C per hour

$DT1_k := DERcd(T1)$ $DT1_0 := 0$ $DT1_{ll} := DERfd(T1)$ $DT1_{lh} := DT1_{lh-1}$ $M3_{j,0} := DT1_j$

$DT2_k := DERcd(T2)$ $DT2_0 := 0$ $DT2_{ll} := DERfd(T2)$ $DT2_{lh} := DT2_{lh-1}$ $M3_{j,1} := DT2_j$

$DT3_k := DERcd(T3)$ $DT3_0 := 0$ $DT3_{ll} := DERfd(T3)$ $DT3_{lh} := DT3_{lh-1}$ $M3_{j,2} := DT3_j$

$DT4_k := DERcd(T4)$ $DT4_0 := 0$ $DT4_{ll} := DERfd(T4)$ $DT4_{lh} := DT4_{lh-1}$ $M3_{j,3} := DT4_j$

$DT5_k := DERcd(T5)$ $DT5_0 := 0$ $DT5_{ll} := DERfd(T5)$ $DT5_{lh} := DT5_{lh-1}$ $M3_{j,4} := DT5_j$

$DT6_k := DERcd(T6)$ $DT6_0 := 0$ $DT6_{ll} := DERfd(T6)$ $DT6_{lh} := DT6_{lh-1}$ $M3_{j,5} := DT6_j$

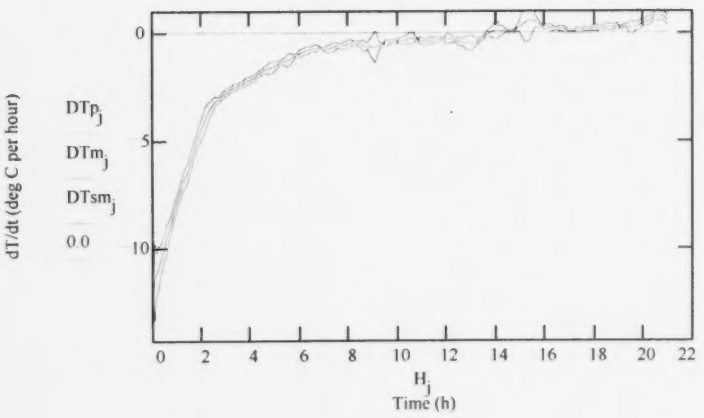
$DTav_j := AVG(M3)$ $DTvar_j := VARE(M3, DTav)$ $DTse_j := STERR(DTvar)$

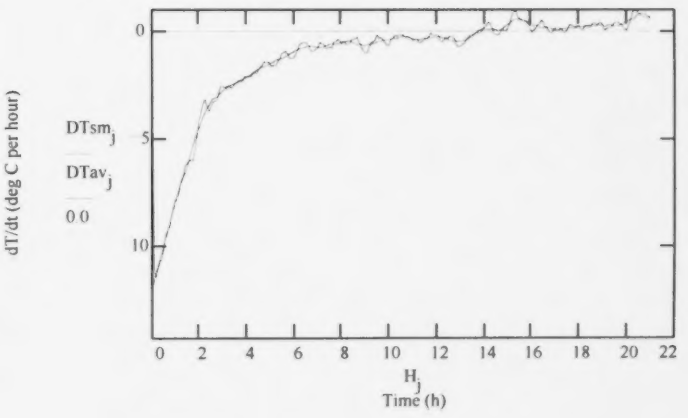
$DTp_j := DTsm_j + DTse_j$ $DTm_j := DTsm_j - DTse_j$ $DTmn := min(DTav)$ $DTmn = 11.548$ $DTmx := max(DTav)$ $DTmx = 0.982$

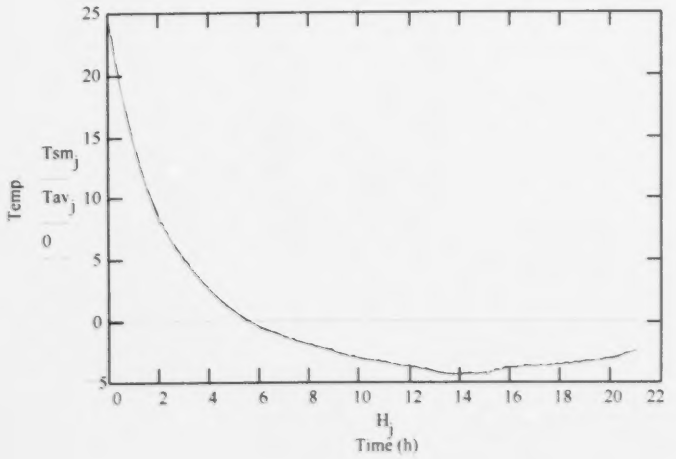
$MDTvar := mean(DTvar)$

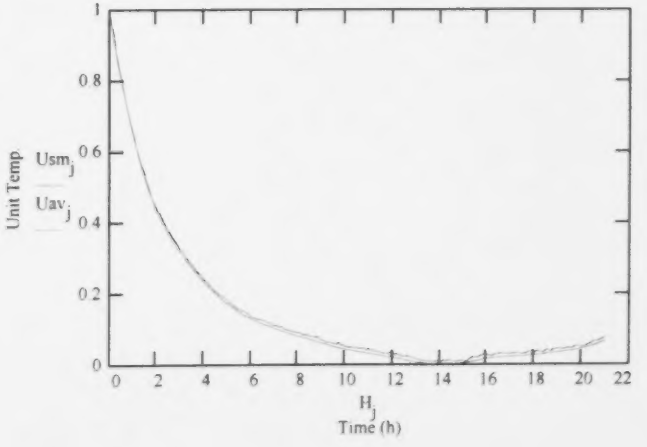
$min(DTsm) = -12.119$ $max(DTsm) = 0.81$

Stnd. error of mean unit variance: $SEMDT := \sqrt{\dfrac{MDTvar}{nr}}$ $SEMDT = 0.302$ $min(DTav) = -11.548$ $max(DTav) = 0.982$


dT/dt (deg C per hour)
DTp_j
DTm_j
DTsm_j
0 0
0
5
10
0 2 4 6 8 10 12 14 16 18 20 22
H_j
Time (h)


dT/dt (deg C per hour)
DTsm_j
DTav_j
0 0
0
5
10
0 2 4 6 8 10 12 14 16 18 20 22
H_j
Time (h)


Temp
Tsm_j
Tav_j
0
25
20
15
10
5
0
-5
0 2 4 6 8 10 12 14 16 18 20 22
H_j
Time (h)


Unit Temp
Usm_j
Uav_j
0 0
1
0.8
0.6
0.4
0.2
0
0 2 4 6 8 10 12 14 16 18 20 22
H_j
Time (h)

Time for Muscle Temperature to reach Ta degrees Celsius based on smoothed curve: $Ta = 10$

$Ja_j := JF(Tsm, Ta)$ $jam := max(Ja)$ $jam = 20$ $\theta_{jam} = 100$ $\theta_{jam+1} = 105$

$\theta asm := \Theta F(\theta_{jam}, \theta_{jam+1}, Tsm_{jam}, Tsm_{jam+1}, Ta)$ $Hasm := \frac{\theta asm}{60}$

Time: $\theta asm = 102.43$ min $Hasm = 1.707$ h $\theta avar = 179.005$ $\theta ase = 5.462$ min.

$\theta aav = 102.29$ $Haav = 1.705$ $\theta asd = 13.379$ $Hase = 0.091$ h.

Time for Muscle Temperature to reach Tb degrees Celsius based on smoothed curve: $Tb = 0$

$Jb_j := JF(Tsm, Tb)$ $jmax := max(Jb)$ $jbm := if(jmax<N, jmax, N-1)$ $\theta_{jbm} = 330$ $\theta_{jbm+1} = 335$

$\theta bp := \frac{\ln(Tb+10) - \ln(A_{N-1})}{B_{N-1}}$ $\theta bp = 1448.915$ $Hbp := \frac{\theta bp}{60}$ $Hbp = 24.149$

$\theta bsm := \Theta F(\theta_{jbm}, \theta_{jbm+1}, Tsm_{jbm}, Tsm_{jbm+1}, Tb)$ $Hbs := \frac{\theta bsm}{60}$ $Hbsm := if(\theta_{jbm} > 1255, Hbp, Hbs)$

Time: $\theta bsm = 332.79$ min $Hbsm = 5.547$ h $\theta bvar = 2234.167$ $\theta bse = 19.297$ min.

$\theta bav = 325.83$ $Hbav = 5.431$ $\theta bsd = 47.267$ $Hbse = 0.322$ h.

Regression & Averaging Summary:

Number of runs used: $nr = 6$

Regression radius: $p = 7$

(No. points in regression) $p + p1 = 15$

Data column no. $nt = 3$

$\frac{\theta_{jbm+1}}{60} = 5.583$

File of Averages and Stnd. Errors (output):

Average & standard error (actual and scaled):

$P_{j,0} = H_j \quad P_{j,1} = Tsm_j \quad P_{j,2} = Tse_j$

$P_{j,3} = Usm_j \quad P_{j,4} = Use_j$

Slope profile:

$R_{j,0} = H_j \quad R_{j,1} = DTsm_j$

$R_{j,2} = DTse_j$

File of Original Data (output):

$Q_{j,0} = H_j \quad Q_{j,1} = T1_j \quad Q_{j,2} = T2_j \quad Q_{j,3} = T3_j$

$Q_{j,4} = T4_j \quad Q_{j,5} = T5_j \quad Q_{j,6} = T6_j$

nr = 6

Output files:

PRNCOLWIDTH = 14 PRNPRECISION = 6 WRITEPRN(13lstavg) = P WRITEPRN(13lstslp) = R

PRNCOLWIDTH = 10 PRNPRECISION = 5 WRITEPRN(13lst_x6) = Q

SEPTEMBER 16, 1994 SEP16.WB1

TIME	TTMA	TMMA	TLST	TNKT	TLCT	THST	THMT	THDT	WTT	TDCA	TLSC	TNKC	TLCC	THSC	THMC	THDC	WTC	TPI	TPO	TAI	TAO	TAMB	MP	UA
0	33.50	33.00	24.75	39.25	38.25	22.00	39.75	40.25	139.30	-2.38	-1.16	-0.21	-0.91	-0.56	-1.14	25.49	147.97	-13.75	20.25	18.50	18.75	17.88	0.00	5.00
5	32.96	33.00	24.50	39.00	38.25	22.50	39.50	40.25	139.30	-2.00	13.59	36.79	34.53	13.94	36.54	38.05	149.04	-13.50	20.25	17.50	18.75	17.88	7.08	3.50
10	32.41	32.15	22.75	39.00	38.00	20.00	39.50	40.50	139.19	-1.25	12.40	37.04	34.53	12.25	36.23	38.49	149.15	-22.75	19.00	13.25	15.25	17.88	0.00	4.10
15	31.87	31.75	22.00	39.00	37.75	19.25	39.25	40.50	139.19	-0.94	11.59	36.98	34.22	11.50	35.86	38.61	149.15	-20.25	16.75	12.25	14.25	17.88	3.36	4.15
20	31.33	31.25	21.00	38.75	37.25	18.00	39.25	40.75	139.08	-0.13	11.27	36.79	33.72	11.13	35.42	38.67	149.15	-27.25	15.00	9.75	12.00	17.88	0.00	4.16
25	30.81	30.60	20.00	38.25	36.75	16.50	39.25	40.50	139.08	-0.50	10.96	36.60	33.16	10.81	35.04	38.80	149.04	-27.25	12.00	7.00	10.00	17.94	4.15	4.21
30	30.29	30.30	19.50	38.25	36.50	15.75	39.00	40.75	138.98	-1.25	10.15	36.29	32.47	10.00	34.67	38.86	149.04	-23.50	9.75	6.00	8.50	17.94	2.26	4.19
35	29.78	29.75	18.50	38.00	36.25	14.50	38.75	40.75	138.98	-0.63	9.84	36.10	31.84	9.88	34.23	38.80	149.04	-23.75	7.75	4.25	6.50	18.06	5.80	4.18
40	29.28	29.30	17.75	37.75	35.75	13.75	38.50	40.75	138.87	0.31	10.09	35.79	31.28	9.88	33.86	38.86	148.93	-24.75	6.50	3.25	5.25	18.19	6.29	4.27
45	28.69	28.70	16.75	37.25	35.00	12.75	38.25	40.75	138.87	-1.75	9.15	35.48	30.59	9.31	33.48	38.86	148.83	-27.75	3.50	0.75	3.50	18.25	6.29	4.26
50	28.21	28.30	16.00	37.00	34.75	11.75	38.25	40.75	138.98	-0.94	9.15	35.23	29.91	9.31	33.11	38.99	148.93	-24.75	3.50	0.50	2.50	18.25	5.80	4.22
55	27.73	27.85	15.25	36.75	34.00	11.25	38.00	40.75	138.87	0.00	9.15	34.85	29.34	9.31	32.61	38.80	148.83	-27.25	2.25	-0.50	1.75	18.25	9.52	4.24
60	27.27	27.30	14.25	36.50	33.75	10.00	37.75	40.75	138.87	-0.94	8.96	34.54	28.66	9.06	32.23	38.86	148.83	-27.50	0.75	-1.75	0.00	18.25	3.97	4.22
65	26.81	26.95	13.75	36.25	33.00	9.75	37.50	40.75	138.87	-1.19	8.46	34.29	28.09	8.81	31.86	38.80	148.83	-28.00	0.25	-2.00	0.25	18.25	13.13	4.29
70	26.35	26.40	13.00	36.00	32.50	8.50	37.25	40.75	138.87	-0.63	8.40	33.91	27.41	8.69	31.48	38.86	148.72	-25.75	-3.00	-4.25	-2.00	18.25	7.39	4.23
75	25.91	26.10	12.50	35.50	32.00	8.25	37.00	40.75	138.87	0.38	8.59	33.60	26.91	9.00	31.23	38.86	148.83	-24.75	-0.75	-3.00	-1.25	18.25	11.36	4.30
80	25.47	25.50	11.50	35.25	31.25	7.25	36.75	40.75	138.76	-2.06	7.90	33.23	26.16	8.38	30.79	38.80	148.72	-28.75	-8.25	-7.00	-4.00	18.25	11.48	4.30
85	25.04	25.15	11.00	34.75	30.75	6.75	36.50	40.75	138.76	-1.00	7.90	32.85	25.66	8.31	30.42	38.80	148.72	-25.25	-3.75	-5.25	-3.75	18.31	7.33	4.24
90	24.61	24.90	10.75	34.50	30.25	6.50	36.25	40.75	138.76	0.19	8.71	32.54	25.09	8.81	30.04	38.80	148.72	-28.25	-7.25	-6.75	-4.25	18.31	20.76	4.30
95	24.19	24.25	9.75	34.00	29.50	5.25	36.00	40.75	138.76	-0.13	9.09	32.29	24.59	9.38	29.86	38.61	148.61	-26.25	-8.25	-8.25	-6.00	18.69	10.99	4.27
100	23.78	23.95	9.50	33.75	29.00	5.00	35.75	40.50	138.76	-0.75	8.77	31.85	23.97	9.31	29.54	38.61	148.61	-27.25	-8.25	-8.00	-6.00	19.19	11.66	4.26
105	23.38	23.60	9.00	33.50	28.50	4.50	35.50	40.50	138.76	-0.19	8.77	31.60	23.53	9.31	29.17	38.61	148.61	-28.00	-11.00	-9.25	-7.00	19.38	3.97	4.26
110	22.98	23.25	8.50	33.00	28.00	4.25	35.00	40.50	138.65	0.19	8.90	31.29	23.09	9.56	28.98	38.61	148.50	-27.25	-10.00	-9.00	-7.00	19.50	14.79	4.23
115	22.59	22.75	8.00	32.50	27.25	3.50	34.75	40.25	138.76	-0.44	8.71	30.91	22.59	9.50	28.73	38.49	148.61	-27.75	-13.00	-10.50	-8.25	19.31	6.29	4.21
120	22.20	22.35	7.50	32.25	26.50	3.00	34.50	40.25	138.76	-1.25	8.27	30.54	22.16	9.06	28.42	38.49	148.61	-26.50	-12.25	-10.75	-8.50	19.19	8.00	4.19
125	22.10	22.15	7.25	31.75	26.00	3.25	34.25	40.00	138.65	0.19	7.96	30.29	21.66	8.81	28.11	38.42	148.50	-22.50	-7.75	-8.25	-7.25	19.19	5.86	4.26
130	21.79	22.05	7.25	31.50	25.75	3.25	34.00	40.00	138.65	-1.00	7.59	29.98	21.28	8.56	27.92	38.42	148.50	-25.00	-8.75	-8.75	-7.00	19.31	12.03	4.22
135	21.50	21.70	7.00	31.25	25.00	3.00	33.50	40.00	138.65	-2.50	6.96	29.60	20.66	7.81	27.54	38.24	148.50	-24.50	-10.00	-9.25	-7.75	19.31	12.33	4.21
140	21.20	21.35	6.50	30.75	24.50	2.75	33.25	39.75	138.76	-0.81	7.40	29.29	20.41	8.19	27.23	38.24	148.61	-23.75	-10.50	-9.50	-7.75	19.31	12.64	4.15
145	20.91	21.15	6.25	30.50	24.00	2.75	33.00	39.75	138.65	0.31	7.71	29.04	19.97	8.50	27.04	38.11	148.50	-23.00	-10.25	-9.25	-7.50	19.38	20.27	4.08
150	20.62	20.80	6.00	30.25	23.25	2.50	32.75	39.50	138.55	-2.38	7.09	28.60	19.47	8.00	26.73	38.05	148.40	-21.50	-9.50	-8.75	-7.50	19.38	15.87	4.05
155	20.34	20.60	5.75	29.75	22.75	2.50	32.50	39.50	138.55	-1.00	6.90	28.41	19.22	7.81	26.48	37.86	148.50	-20.50	-10.25	-9.25	-7.50	19.38	18.25	4.08
160	20.06	20.30	5.50	29.50	22.50	2.25	32.00	39.25	138.55	-0.19	6.96	28.16	18.84	8.00	26.17	37.67	148.40	-19.75	-10.75	-9.25	-7.75	19.50	22.95	4.02
165	19.79	20.00	5.00	29.00	22.00	2.25	31.75	39.00	138.55	-1.00	6.96	27.85	18.47	8.00	25.98	37.67	148.40	-19.75	-11.25	-9.50	-7.75	19.50	15.69	4.00
170	19.51	19.75	5.00	28.75	21.25	2.00	31.50	39.00	138.55	-1.25	6.59	27.60	18.03	7.50	25.79	37.49	148.40	-18.75	-10.75	-9.00	-7.50	19.38	21.12	3.96
175	19.24	19.60	4.75	28.50	21.00	2.25	31.25	38.75	138.55	-0.75	6.59	27.16	17.66	7.63	25.48	37.30	148.40	-18.00	-9.75	-9.00	-7.50	19.38	18.56	3.90
180	18.98	19.15	4.25	28.00	20.25	1.75	30.75	38.75	138.55	0.31	6.77	27.10	17.34	8.00	25.29	37.30	148.40	-18.50	-11.25	-9.50	-7.75	19.38	25.15	3.91
185	18.72	19.05	4.25	27.75	20.00	2.00	30.50	38.50	138.44	-1.19	6.77	26.66	17.09	7.81	25.11	36.99	148.29	-18.25	-10.75	-8.75	-7.25	19.31	31.62	3.92
190	18.46	18.95	4.25	27.50	19.50	2.00	30.50	38.50	138.44	0.81	7.27	26.48	16.78	8.50	24.92	36.92	148.40	-17.50	-10.50	-8.75	-7.50	19.38	20.21	4.05
195	18.20	18.55	3.75	27.00	19.00	1.75	30.00	38.25	138.44	-0.19	7.40	26.23	16.47	8.69	24.79	36.74	148.29	-17.00	-10.25	-9.00	-7.50	19.31	22.34	3.94
200	17.95	18.30	3.75	26.75	18.50	1.50	29.75	38.00	138.44	-1.56	6.15	25.91	16.09	7.69	24.48	36.61	148.29	-17.25	-11.00	-9.00	-7.25	19.31	17.83	3.92
205	17.70	18.10	3.50	26.50	18.25	1.50	29.50	37.75	138.44	-0.81	6.09	25.60	15.78	7.63	24.23	36.42	148.29	-16.50	-10.25	-9.00	-7.50	19.31	25.89	3.81

RC3 TREATMENT = L

CS1

210	17.45	17.80	3.25	26.25	17.75	1.25	29.25	37.50	138.44	0.31	6.15	25.35	15.72	7.69	24.11	36.24	148.29	-16.00	-9.75	-8.50	-7.00	19.31	27.90	3.93
215	17.21	17.75	3.25	26.00	17.50	1.50	29.00	37.50	138.44	-2.63	5.59	25.04	15.28	7.19	23.86	36.17	148.29	-16.25	-10.75	-9.00	-7.25	19.19	34.92	3.92
220	16.97	17.35	2.75	25.50	17.00	1.25	28.50	37.25	138.44	-1.00	5.65	24.73	14.97	7.44	23.73	35.99	148.29	-16.00	-10.50	-8.75	-7.50	19.19	31.50	3.96
225	16.73	17.20	2.75	25.25	16.50	1.00	28.50	37.25	138.33	-0.13	5.65	24.54	14.78	7.44	23.54	35.86	148.29	-15.75	-11.00	-9.00	-7.50	19.19	29.85	3.91
230	16.50	16.95	2.50	25.00	16.25	1.00	28.25	36.75	138.33	-1.25	5.65	24.29	14.59	7.50	23.36	35.67	148.18	-15.25	-10.25	-8.75	-7.25	19.13	36.02	3.87
235	16.27	16.75	2.50	24.75	15.75	1.00	27.75	36.75	138.33	-1.25	5.27	23.98	14.28	7.13	23.17	35.49	148.29	-15.25	-10.50	-9.00	-7.50	19.13	36.08	3.92
240	16.04	16.55	2.25	24.50	15.50	1.00	27.50	36.50	138.33	-0.63	5.27	23.79	14.09	7.31	22.92	35.24	148.29	-15.00	-10.50	-8.75	-7.50	19.13	38.34	3.86
245	15.82	16.25	2.00	24.25	15.00	0.75	27.25	36.25	138.33	0.31	5.46	23.60	13.91	7.50	22.86	35.17	148.18	-15.00	-10.50	-8.75	-7.50	19.13	38.34	3.86
250	15.59	16.05	1.75	23.75	14.75	0.75	27.00	36.00	138.33	-2.31	4.84	23.29	13.47	7.00	22.67	34.99	148.18	-14.75	-10.50	-8.75	-7.50	19.13	39.01	3.70
255	15.38	15.90	1.75	23.50	14.50	0.75	26.75	35.75	138.22	-1.00	4.96	23.10	13.28	7.13	22.36	34.80	148.18	-14.75	-10.50	-8.75	-7.50	19.13	39.01	3.86
260	15.16	15.70	1.50	23.25	14.00	0.50	26.75	35.75	138.33	-0.13	5.02	22.91	13.22	7.19	22.29	34.61	148.18	-14.75	-10.75	-8.75	-7.25	19.13	43.65	3.82
265	14.94	15.50	1.50	23.00	13.75	0.50	26.25	35.50	138.33	-1.25	4.96	22.60	12.91	7.13	22.04	34.42	148.18	-14.50	-10.50	-8.75	-7.50	19.00	42.74	3.86
270	14.73	15.25	1.25	22.75	13.25	0.25	26.25	35.25	138.33	-1.25	4.52	22.41	12.72	6.81	21.86	34.24	148.18	-14.50	-10.75	-9.00	-7.50	19.13	39.99	3.91
275	14.52	15.05	1.00	22.50	13.00	0.25	26.00	35.00	138.22	-0.75	4.65	22.23	12.53	6.94	21.67	34.11	148.18	-14.25	-10.25	-8.75	-7.50	19.00	34.98	3.87
280	14.32	14.90	1.00	22.25	12.75	0.25	25.75	34.75	138.22	0.19	4.84	22.04	12.28	7.19	21.48	33.86	148.18	-14.00	-10.25	-8.50	-7.25	19.13	40.11	3.86
285	14.11	14.75	1.00	22.00	12.50	0.25	25.25	34.75	138.22	-2.50	4.34	21.73	11.97	6.69	21.36	33.67	148.18	-14.00	-10.50	-8.75	-7.50	19.13	42.80	3.83
290	13.91	14.45	0.75	21.50	12.00	0.25	25.00	34.25	138.22	-1.19	4.34	21.54	11.84	6.81	21.17	33.49	148.07	-13.75	-9.75	-8.50	-7.00	19.00	41.45	3.84
295	13.72	14.35	0.75	21.25	11.50	0.25	25.00	34.25	138.22	-0.31	4.46	21.35	11.66	6.94	20.98	33.30	148.07	-13.75	-10.50	-8.50	-7.00	19.13	44.75	3.80
300	13.52	14.20	0.75	21.25	11.25	0.25	24.75	34.00	138.22	-0.50	4.52	21.16	11.47	7.13	20.79	33.17	148.07	-13.75	-10.25	-8.75	-7.25	19.13	41.82	3.81
305	13.36	14.05	0.50	21.00	11.25	0.00	24.50	33.75	138.22	-1.69	4.02	20.91	11.16	6.50	20.73	32.99	148.18	-13.75	-10.25	-8.50	-7.25	19.13	44.20	3.76
310	13.17	13.80	0.50	20.75	10.75	0.00	24.25	33.50	138.22	-0.94	4.15	20.66	10.97	6.69	20.48	32.67	148.07	-14.00	-10.75	-8.75	-7.25	19.00	60.74	3.71
315	12.98	13.50	0.25	20.25	10.25	-0.25	24.00	33.25	138.22	0.00	4.34	20.54	10.84	6.94	20.29	32.49	148.07	-13.75	-11.00	-9.00	-7.50	19.13	60.74	3.85
320	12.80	13.35	0.25	20.00	10.25	-0.50	23.75	33.00	138.12	-1.75	4.02	20.23	10.53	6.69	20.23	32.30	147.97	-13.50	-10.75	-9.00	-7.50	19.13	60.74	3.78
325	12.61	13.15	0.00	19.75	9.75	-0.25	23.50	32.75	138.12	-1.25	3.84	20.04	10.34	6.50	19.92	32.24	148.07	-13.50	-10.75	-9.00	-7.50	19.13	60.74	3.71
330	12.43	12.95	0.00	19.75	9.50	-0.50	23.25	32.50	138.22	-0.75	3.84	19.85	10.16	6.50	19.79	32.05	148.07	-13.50	-10.75	-9.00	-7.50	19.13	60.81	3.69
335	12.25	12.75	-0.25	19.25	9.25	-0.75	23.00	32.50	138.22	0.19	4.02	19.79	10.03	6.81	19.61	31.86	148.07	-13.25	-10.75	-9.00	-7.50	19.13	60.62	3.80
340	12.07	12.70	-0.25	19.00	9.00	-0.50	23.00	32.25	138.12	-2.50	3.65	19.60	9.78	6.44	19.61	31.74	148.07	-13.50	-10.75	-9.00	-7.50	19.19	60.74	3.73
345	11.90	12.40	-0.50	18.75	8.50	-0.75	22.75	32.00	138.12	-1.19	3.65	19.35	9.66	6.44	19.36	31.42	148.07	-13.25	-10.50	-8.75	-7.50	19.31	60.74	3.72
350	11.72	12.40	-0.25	18.50	8.50	-0.50	22.50	31.75	138.12	-0.50	3.65	19.10	9.47	6.50	19.17	31.24	148.07	-13.50	-10.75	-9.00	-7.50	19.19	60.81	3.73
355	11.55	12.15	-0.50	18.50	8.25	-0.75	22.25	31.50	138.12	0.19	3.84	19.10	9.34	6.69	19.11	31.05	148.07	-13.25	-10.75	-9.00	-7.50	19.19	60.93	3.71
360	11.38	11.85	-0.75	18.25	7.75	-1.00	22.00	31.25	138.12	-1.88	3.21	18.79	9.09	6.31	18.86	30.99	147.97	-13.25	-10.75	-9.00	-7.50	19.13	60.99	3.70
365	11.22	11.75	-0.75	18.00	7.75	-1.00	21.75	31.00	138.12	-0.94	3.34	18.60	8.91	6.44	18.79	30.67	148.07	-13.50	-10.75	-9.25	-7.75	19.13	61.05	3.69
370	11.05	11.55	-0.75	17.75	7.25	-1.00	21.50	30.75	138.12	-0.19	3.40	18.48	8.78	6.44	18.61	30.61	148.07	-13.50	-10.75	-9.25	-7.75	19.00	61.05	3.82
375	10.89	11.50	-0.75	17.50	7.25	-0.75	21.25	30.50	138.12	-1.19	3.40	18.29	8.59	6.44	18.61	30.30	147.97	-13.25	-10.75	-7.75	-6.75	18.88	60.93	3.46
380	10.73	11.30	-1.00	17.25	6.75	-0.75	21.25	30.25	138.12	-1.38	3.02	18.10	8.41	6.13	18.36	30.24	147.97	-13.00	-10.75	-9.00	-7.50	18.88	61.05	4.47
385	10.57	11.20	-1.00	17.00	6.50	-0.75	21.00	30.25	138.12	-0.81	3.15	18.04	8.28	6.19	18.11	29.92	148.07	-13.25	-10.50	-8.75	-7.50	18.81	61.17	4.52
390	10.41	11.00	-1.00	16.75	6.25	-0.75	20.75	29.75	138.12	0.00	3.34	17.85	8.16	6.44	18.11	29.74	147.97	-13.25	-9.75	-7.50	-6.75	18.69	61.17	4.42
395	10.26	11.05	-0.75	16.75	6.25	-0.50	20.50	29.75	138.01	-1.88	3.02	17.66	7.97	6.19	17.92	29.67	147.97	-13.25	-10.00	-7.75	-6.75	18.69	61.17	4.38
400	10.10	10.90	-0.75	16.50	6.00	-0.50	20.25	29.50	138.01	-1.25	2.84	17.54	7.78	6.00	17.79	29.55	147.97	-13.25	-10.25	-8.25	-7.00	18.63	61.17	4.40
405	9.95	10.70	-1.00	16.25	5.75	-0.50	20.00	29.25	138.12	-0.75	2.84	17.35	7.59	6.13	17.61	29.36	147.97	-13.00	-10.00	-8.25	-7.00	18.63	61.17	4.39
410	9.80	10.50	-1.25	16.00	5.50	-0.75	20.00	29.00	138.01	0.19	3.15	17.16	7.47	6.31	17.48	29.17	147.97	-12.75	-10.25	-8.50	-7.00	18.63	61.17	4.45
415	9.66	10.35	-1.25	15.75	5.25	-0.75	19.75	28.75	138.01	-2.50	2.52	16.98	7.28	5.88	17.42	29.05	147.97	-13.00	-10.25	-8.50	-7.25	18.50	61.11	4.41
420	9.51	10.20	-1.25	15.75	5.00	-0.75	19.50	28.50	138.01	-1.19	2.65	16.85	7.16	6.00	17.29	28.80	147.97	-12.75	-10.25	-8.50	-7.25	18.50	61.17	4.41
425	9.37	10.20	-1.25	15.50	5.00	-0.75	19.50	28.50	138.01	-0.44	2.71	16.79	7.09	6.00	17.11	28.61	147.97	-12.75	-10.25	-8.75	-7.50	18.50	61.17	4.40

FST

430	9.25	9.95	-1.25	15.25	4.75	-1.00	19.25	28.00	138.12	0.00	2.90	16.66	6.97	6.31	16.98	28.42	147.97	-12.75	-10.25	-8.75	-7.50	18.50	55.98	4.39
435	9.11	9.80	-1.50	15.25	4.50	-1.00	19.00	28.00	138.01	-1.75	2.34	16.48	6.78	5.81	16.92	28.24	147.86	-12.75	-10.25	-8.75	-7.50	18.44	56.04	4.41
440	9.00	9.70	-1.50	15.00	4.50	-1.00	18.75	27.75	138.01	-1.00	2.46	16.29	6.66	5.81	16.79	27.92	147.86	-12.75	-10.25	-8.75	-7.50	18.31	55.98	4.42
445	8.87	9.45	-1.75	14.75	4.25	-1.25	18.50	27.50	138.01	-0.44	2.52	16.16	6.59	5.88	16.61	27.80	147.97	-12.75	-10.25	-8.75	-7.50	18.25	45.60	4.40
450	8.73	9.45	-1.50	14.75	4.00	-1.00	18.50	27.25	138.12	-0.13	2.84	15.98	6.47	6.19	16.48	27.74	147.97	-13.00	-10.00	-8.50	-7.25	18.19	50.98	4.42
455	8.60	9.20	-2.00	14.50	4.00	-1.25	18.25	27.00	138.01	-0.94	2.65	15.85	6.28	6.31	16.42	27.55	147.86	-13.00	-10.25	-9.00	-7.50	18.06	55.07	4.44
460	8.46	9.05	-2.00	14.25	3.75	-1.25	18.00	26.75	138.01	-0.31	2.65	15.66	6.16	6.50	16.23	27.36	147.86	-13.00	-10.25	-9.00	-7.50	17.94	52.44	4.37
465	8.33	8.90	-2.00	14.25	3.50	-1.25	17.75	26.50	138.01	-0.13	2.90	15.66	6.09	6.63	16.23	27.17	147.86	-13.00	-10.25	-9.00	-7.75	17.75	47.50	4.39
470	8.20	8.85	-2.00	14.00	3.50	-1.25	17.75	26.25	138.01	-0.81	2.71	15.48	5.97	6.63	16.11	26.99	147.97	-13.25	-10.50	-9.00	-7.75	17.75	53.05	4.40
475	8.08	8.70	-2.00	13.75	3.25	-1.50	17.50	26.25	138.01	-1.25	2.52	15.35	5.78	6.50	15.92	26.86	147.86	-13.25	-10.75	-9.25	-8.00	17.69	55.74	4.41
480	7.95	8.50	-2.25	13.50	3.00	-1.50	17.25	26.00	138.01	-0.13	2.71	15.16	5.78	6.63	15.92	26.55	147.86	-13.25	-10.50	-9.00	-7.75	17.56	48.78	4.36
485	7.83	8.40	-2.25	13.25	3.00	-1.50	17.00	25.75	138.01	-2.94	2.15	15.10	5.53	5.88	15.79	26.55	147.86	-13.25	-10.50	-9.25	-8.00	17.44	43.23	4.39
490	7.70	8.20	-2.50	13.25	2.75	-1.75	17.00	25.50	138.01	-1.19	2.15	14.91	5.53	5.81	15.61	26.36	147.86	-13.25	-10.50	-9.25	-8.00	17.38	47.68	4.34
495	7.58	8.10	-2.50	13.25	2.75	-1.75	16.75	25.25	138.01	-0.50	2.21	14.79	5.47	5.88	15.48	26.05	147.86	-13.25	-10.50	-9.00	-7.75	17.25	47.62	4.40
500	7.46	8.00	-2.50	13.00	2.75	-1.75	16.50	25.00	138.01	-0.19	2.46	14.79	5.34	5.88	15.42	25.99	147.86	-13.25	-10.50	-9.00	-7.75	17.25	47.56	4.37
505	7.35	7.80	-2.50	12.75	2.25	-2.00	16.50	24.75	138.01	-1.88	1.84	14.60	5.16	5.38	15.29	25.80	147.86	-13.50	-10.50	-9.25	-8.00	17.19	47.25	4.39
510	7.23	7.70	-2.50	12.75	2.25	-2.00	16.25	24.50	138.01	-1.00	1.90	14.48	5.16	5.50	15.23	25.67	147.86	-13.25	-10.50	-9.25	-8.00	17.19	45.48	4.37
515	7.11	7.65	-2.50	12.50	2.25	-2.00	16.00	24.50	138.01	-0.19	2.15	14.29	5.03	5.69	15.04	25.61	147.75	-13.50	-10.50	-9.25	-8.00	17.06	51.77	4.38
520	7.00	7.50	-2.50	12.25	2.00	-2.00	15.75	24.25	138.01	-1.50	2.02	14.29	4.97	5.69	14.92	25.36	147.86	-13.50	-10.75	-9.50	-8.00	17.00	51.71	4.38
525	6.89	7.40	-2.75	12.00	2.00	-2.00	15.75	24.00	138.01	-1.25	1.84	14.10	4.84	5.38	14.79	25.17	147.86	-13.50	-10.50	-9.25	-8.25	17.00	45.91	4.35
530	6.78	7.70	-1.75	12.00	2.00	-1.00	15.50	23.75	137.90	-1.00	1.84	13.98	4.72	5.50	14.73	24.92	147.75	-13.75	-9.25	-6.75	-2.75	16.98	60.44	4.37
535	6.67	7.40	-2.25	11.75	1.75	-1.50	15.25	23.75	137.90	-0.63	1.90	13.91	4.66	5.50	14.61	24.74	147.75	-13.75	-11.00	-9.50	-6.25	16.98	55.74	4.33
540	6.56	6.85	-3.25	11.50	1.50	-2.75	15.25	23.50	137.90	-0.31	2.02	13.79	4.66	5.63	14.54	24.61	147.75	-13.00	-11.00	-10.25	-11.00	16.88	34.07	4.39
545	6.45	6.60	-3.50	11.50	1.50	-3.25	15.00	23.25	137.90	-0.13	2.02	13.66	4.66	5.63	14.42	24.30	147.86	-13.00	-10.50	-10.25	-11.25	16.88	25.46	4.42
550	6.35	6.50	-3.75	11.25	1.50	-3.25	15.00	23.00	138.01	-0.13	2.02	13.60	4.41	5.63	14.29	24.24	147.86	-12.50	-9.50	-10.00	-11.00	16.88	18.07	4.35
555	6.24	6.25	-4.00	11.00	1.25	-3.50	14.75	22.75	138.01	-0.13	2.02	13.48	4.41	5.69	14.29	24.11	147.75	-12.75	-9.75	-10.25	-11.00	17.00	14.71	4.30
560	6.14	6.15	-4.00	11.00	1.25	-3.75	14.50	22.75	138.01	-1.50	1.52	13.16	4.34	5.19	14.23	23.92	147.75	-12.75	-9.50	-10.00	-10.75	17.06	13.98	4.22
565	6.04	6.05	-4.00	11.00	1.25	-3.75	14.25	22.50	137.90	-1.00	1.52	13.16	4.34	5.19	14.04	23.74	147.75	-13.25	-9.50	-9.75	-10.75	17.19	6.47	4.25
570	5.94	5.95	-4.00	10.75	1.00	-3.75	14.25	22.25	137.90	-0.75	1.59	13.10	4.22	5.31	13.92	23.67	147.75	-13.00	-8.75	-9.50	-10.25	17.19	10.07	4.24
575	5.84	5.85	-4.00	10.50	1.00	-3.75	14.00	22.00	137.90	-0.50	1.59	12.98	4.16	5.38	13.92	23.55	147.75	-13.25	-8.50	-9.25	-10.25	17.19	10.01	4.17
580	5.74	5.85	-4.00	10.50	1.00	-3.75	14.00	22.00	137.90	-0.44	1.71	12.91	4.03	5.38	13.79	23.36	147.75	-13.75	-8.50	-9.25	-10.25	17.25	12.76	4.14
585	5.64	5.70	-3.75	10.25	0.75	-4.00	13.75	21.75	137.90	-0.31	1.71	12.66	3.91	5.38	13.61	23.24	147.75	-14.00	-9.25	-9.75	-10.50	17.25	10.87	4.20
590	5.55	5.55	-4.00	10.00	0.75	-4.00	13.50	21.50	137.90	-0.19	1.71	12.60	3.84	5.38	13.54	22.99	147.75	-14.75	-9.75	-10.00	-10.50	17.38	13.19	4.23
595	5.45	5.40	-4.25	10.00	0.50	-4.25	13.50	21.50	137.90	-0.19	1.71	12.48	3.84	5.38	13.54	22.99	147.75	-15.25	-10.00	-10.00	-10.75	17.38	13.06	4.25
600	5.36	5.30	-4.25	9.75	0.50	-4.25	13.25	21.25	137.90	-2.63	1.21	12.41	3.72	5.00	13.42	22.74	147.64	-15.50	-10.00	-10.00	-10.75	17.38	8.79	4.29
605	5.27	5.30	-4.00	9.75	0.50	-4.00	13.00	21.00	137.90	-1.00	1.34	12.16	3.59	5.00	13.23	22.55	147.75	-14.75	-9.25	-9.75	-10.50	17.38	8.85	4.29
610	5.18	5.20	-4.25	9.50	0.50	-4.25	13.00	21.00	137.90	-0.31	1.52	12.16	3.59	5.13	13.11	22.49	147.75	-16.50	-10.50	-10.25	-10.75	17.44	13.49	4.30
615	5.09	5.00	-4.25	9.25	0.25	-4.50	12.75	20.75	137.90	0.00	1.71	12.10	3.59	5.31	13.11	22.36	147.64	-15.75	-10.50	-10.25	-11.00	17.44	7.45	4.25
620	5.00	5.00	-4.25	9.25	0.25	-4.25	12.75	20.50	137.90	-1.38	1.21	11.98	3.53	4.88	13.04	22.11	147.75	-15.00	-9.00	-9.50	-10.25	17.44	7.51	4.32
625	4.91	4.95	-4.25	9.00	0.25	-4.25	12.50	20.50	137.90	-0.19	1.40	11.79	3.41	5.13	12.86	22.11	147.75	-16.75	-9.00	-9.25	-10.00	17.44	15.02	4.29
630	4.83	4.85	-4.00	9.00	0.25	-4.50	12.25	20.25	137.90	-0.94	1.52	11.73	3.34	5.19	12.86	21.99	147.75	-17.00	-10.50	-10.50	-10.75	17.44	11.84	4.29
635	4.74	4.75	-4.25	8.75	0.00	-4.50	12.25	20.25	137.90	-1.19	1.21	11.54	3.22	4.88	12.67	21.67	147.75	-17.25	-10.00	-10.25	-10.75	17.44	6.90	4.32
640	4.66	4.70	-4.25	8.75	0.00	-4.50	12.25	20.00	137.90	-0.13	1.52	11.54	3.34	5.13	12.61	21.61	147.64	-16.00	-10.50	-10.50	-10.75	17.44	6.90	4.28
645	4.58	4.65	-4.25	8.50	0.00	-4.50	12.00	20.00	137.90	-1.50	1.40	11.48	3.22	5.00	12.61	21.61	147.64	-17.25	-9.50	-10.00	-10.50	17.44	10.87	4.25

RC3 TREATMENT = L

650	4.50	4.45	-4.25	8.50	-0.25	-4.75	11.75	19.75	137.90	-0.94	1.21	11.23	3.22	4.81	12.36	21.42	147.64	-18.00	-10.75	-10.50	-10.75	17.44	12.94	4.29
655	4.41	4.35	-4.50	8.25	-0.25	-4.75	11.75	19.50	137.90	0.00	1.52	11.23	3.09	5.00	12.36	21.17	147.64	-17.00	-9.50	-10.00	-10.25	17.44	10.26	4.25
660	4.33	4.40	-4.25	8.00	-0.25	-4.50	11.50	19.50	137.90	-2.00	1.21	11.04	3.03	4.81	12.29	21.11	147.64	-17.50	-9.50	-10.00	-10.25	17.44	10.32	4.24
665	4.26	4.30	-4.50	8.00	-0.25	-4.75	11.50	19.50	137.90	-0.44	1.34	11.04	3.03	5.00	12.17	20.92	147.75	-18.00	-10.75	-10.75	-10.75	17.44	15.32	4.28
670	4.18	4.15	-4.50	8.00	-0.25	-4.75	11.25	19.00	137.90	1.13	1.84	10.85	3.03	5.63	12.11	20.74	147.64	-19.25	-11.50	-11.25	-11.25	17.44	5.68	4.28
675	4.10	4.10	-4.50	7.75	-0.25	-4.75	11.00	19.00	137.90	0.19	2.02	10.73	3.03	5.88	12.11	20.74	147.64	-18.00	-9.75	-10.25	-10.50	17.44	10.87	4.25
680	4.03	4.10	-4.50	7.75	-0.25	-4.75	11.00	19.00	137.90	-1.38	1.09	10.66	2.91	5.00	11.98	20.55	147.64	-18.25	-10.25	-10.50	-10.50	17.44	10.81	4.23
685	3.95	4.00	-4.50	7.50	-0.25	-4.75	10.75	18.75	137.90	-0.13	1.40	10.66	2.91	5.13	11.86	20.55	147.64	-18.25	-10.25	-10.50	-10.50	17.44	10.81	4.25
690	3.88	3.95	-4.50	7.50	-0.25	-4.75	10.75	18.50	137.90	-1.56	1.21	10.54	2.84	4.88	11.79	20.30	147.64	-18.50	-10.25	-10.50	-10.50	17.44	10.81	4.21
695	3.81	3.85	-4.50	7.25	-0.50	-4.75	10.50	18.50	137.90	-0.94	1.09	10.35	2.84	4.63	11.67	20.24	147.64	-19.00	-10.50	-10.50	-10.50	17.44	12.45	4.21
700	3.73	3.85	-4.50	7.25	-0.50	-4.75	10.50	18.50	137.79	0.06	1.40	10.35	2.84	4.81	11.61	20.05	147.64	-19.25	-11.00	-11.00	-10.75	17.44	12.58	4.21
705	3.66	3.70	-4.50	7.25	-0.50	-5.00	10.25	18.25	137.90	-2.06	1.02	10.23	2.66	4.50	11.61	19.92	147.64	-19.25	-11.00	-11.00	-10.75	17.44	12.52	4.27
710	3.59	3.65	-4.50	7.00	-0.50	-5.00	10.25	18.00	137.90	-0.63	1.09	10.16	2.72	4.63	11.48	19.74	147.64	-19.25	-11.25	-11.25	-11.00	17.38	12.52	4.25
715	3.55	3.60	-4.50	7.00	-0.50	-5.00	10.00	18.00	137.90	0.06	1.40	10.16	2.72	4.81	11.36	19.61	147.64	-19.25	-11.25	-11.25	-11.00	17.38	12.45	4.30
720	3.51	3.45	-4.75	6.75	-0.50	-5.25	10.00	17.75	137.90	-1.50	0.90	9.98	2.66	4.50	11.29	19.55	147.64	-19.75	-11.75	-11.50	-11.25	17.38	13.80	4.17
725	3.46	3.40	-4.75	6.50	-0.50	-5.00	9.75	17.50	137.90	-0.44	1.09	9.85	2.66	4.63	11.29	19.55	147.64	-18.75	-11.50	-11.25	-11.25	17.38	7.39	4.19
730	3.39	3.50	-4.50	6.75	-0.50	-4.75	9.75	17.50	137.79	0.06	1.40	9.73	2.66	4.81	11.17	19.36	147.64	-18.00	-9.75	-10.50	-10.50	17.38	10.50	4.25
735	3.32	3.85	-3.75	6.25	-0.50	-3.50	9.50	17.50	137.79	-1.25	0.90	9.66	2.53	4.31	11.11	19.17	147.64	-19.75	-11.75	-10.00	-3.50	17.38	37.18	4.10
740	3.26	3.25	-4.50	6.25	-0.75	-5.00	9.25	17.25	137.79	-0.19	1.21	9.54	2.53	4.50	10.98	19.17	147.64	-20.50	-13.75	-12.25	-11.25	17.38	17.64	4.19
745	3.19	3.20	-4.75	6.25	-0.50	-5.00	9.25	17.00	137.90	-0.50	1.40	9.54	2.53	4.69	10.86	18.99	147.64	-19.00	-11.75	-11.75	-11.25	17.25	9.16	4.18
750	3.13	3.25	-4.50	6.25	-0.50	-5.00	9.25	17.00	137.90	-1.00	0.90	9.48	2.41	4.38	10.98	18.86	147.64	-19.25	-10.75	-11.00	-10.50	17.38	14.35	4.16
755	3.07	3.10	-4.75	5.75	-0.50	-5.00	9.00	16.75	137.90	0.00	1.21	9.48	2.53	4.50	10.79	18.74	147.64	-18.00	-11.25	-11.25	-10.75	17.38	8.67	4.20
760	3.00	3.15	-4.50	6.00	-0.50	-5.00	9.00	16.75	137.90	-1.00	1.21	9.23	2.41	4.50	10.79	18.67	147.64	-19.75	-10.75	-10.75	-10.50	17.38	21.25	4.17
765	2.94	2.95	-4.75	5.75	-0.75	-5.00	8.75	16.50	137.79	-0.94	0.90	9.16	2.34	4.19	10.67	18.55	147.64	-18.25	-11.25	-11.25	-10.75	17.25	14.41	4.15
770	2.88	3.00	-4.75	5.50	-0.50	-5.00	8.75	16.50	137.79	0.19	1.34	9.16	2.41	4.38	10.48	18.36	147.64	-18.25	-11.50	-11.25	-10.75	17.25	9.95	4.16
775	2.82	2.95	-4.50	5.75	-0.50	-5.00	8.50	16.25	137.79	-2.00	1.02	9.04	2.34	4.06	10.48	18.36	147.54	-19.00	-11.00	-10.75	-10.50	17.25	14.53	4.17
780	2.76	2.85	-4.75	5.50	-0.50	-5.25	8.50	16.25	137.79	-1.25	0.77	8.98	2.22	4.00	10.36	18.17	147.54	-18.75	-11.50	-11.25	-10.75	17.25	13.31	4.18
785	2.71	2.70	-4.75	5.25	-0.75	-5.25	8.25	16.00	137.79	-0.44	1.09	8.85	2.22	4.06	10.29	18.05	147.54	-18.75	-11.50	-11.25	-10.75	17.25	13.43	4.17
790	2.65	2.65	-4.75	5.25	-0.75	-5.25	8.25	15.75	137.79	0.19	1.34	8.85	2.34	4.31	10.29	17.99	147.54	-18.25	-11.00	-11.00	-10.50	17.25	11.11	4.13
795	2.59	2.70	-4.75	5.25	-0.75	-5.00	8.25	15.75	137.79	-2.06	0.71	8.73	2.09	3.75	10.29	17.99	147.54	-19.00	-11.25	-11.00	-10.50	17.25	14.71	4.15
800	2.54	2.55	-4.75	5.00	-0.75	-5.25	8.00	15.50	137.79	-1.19	0.77	8.66	2.22	3.88	10.17	17.80	147.54	-19.25	-11.50	-11.25	-10.75	17.25	17.52	4.14
805	2.48	2.55	-5.00	5.00	-0.50	-5.25	8.00	15.50	137.79	-0.31	1.09	8.54	2.09	4.00	10.11	17.67	147.54	-19.25	-12.50	-11.75	-11.00	17.25	16.67	4.09
810	2.43	2.45	-5.00	5.00	-0.50	-5.25	7.75	15.25	137.79	0.50	1.34	8.54	2.22	4.38	10.11	17.67	147.54	-20.00	-12.25	-11.50	-10.75	17.25	9.71	4.12
815	2.37	2.35	-5.00	4.75	-0.75	-5.25	7.75	15.00	137.79	-1.00	1.09	8.48	2.03	4.38	9.98	17.61	147.54	-18.00	-10.25	-10.75	-10.50	17.19	9.77	4.14
820	2.32	2.35	-4.75	4.75	-0.75	-5.25	7.50	15.00	137.79	0.94	1.40	8.48	2.09	4.69	9.86	17.61	147.54	-19.50	-11.50	-11.00	-10.25	17.19	18.25	4.09
825	2.27	2.20	-5.00	4.50	-0.75	-5.50	7.50	14.75	137.79	-0.31	1.21	8.35	2.09	4.81	9.86	17.42	147.54	-19.75	-13.00	-11.75	-11.00	17.19	10.62	4.15
830	2.22	2.35	-4.75	4.50	-0.50	-5.25	7.50	14.75	137.79	-1.25	1.02	8.29	2.03	4.69	9.79	17.42	147.54	-19.00	-11.25	-11.25	-10.50	17.19	17.64	4.09
835	2.17	2.15	-5.00	4.25	-0.75	-5.25	7.25	14.50	137.79	0.19	1.21	8.29	2.09	4.69	9.67	17.24	147.54	-18.75	-11.25	-11.25	-10.75	17.19	12.15	4.11
840	2.12	2.20	-4.75	4.25	-0.75	-5.25	7.25	14.50	137.79	-1.19	1.02	8.16	2.03	4.63	9.67	17.24	147.54	-19.00	-11.25	-11.25	-10.50	17.19	13.31	4.11
845	2.07	2.05	-5.00	4.25	-0.75	-5.25	7.00	14.25	137.79	-1.00	0.90	8.10	2.03	4.00	9.61	17.05	147.54	-18.00	-10.00	-10.50	-10.00	17.19	9.52	4.12
850	2.02	2.05	-4.75	4.25	-0.75	-5.25	7.00	14.00	137.79	-0.44	1.02	7.98	2.03	4.06	9.61	17.05	147.54	-19.50	-12.00	-11.25	-10.50	17.19	18.50	4.12
855	1.97	1.95	-5.00	4.00	-0.75	-5.25	6.75	14.00	137.79	0.31	1.21	7.85	2.03	4.19	9.48	16.86	147.54	-18.75	-11.75	-11.50	-10.75	17.06	6.78	4.09
860	1.93	2.05	-4.75	4.00	-0.50	-5.00	6.75	13.75	137.69	-1.88	0.59	7.85	1.91	3.69	9.48	16.74	147.54	-19.50	-10.75	-11.00	-10.25	17.19	18.56	4.14
865	1.88	1.95	-4.75	4.00	-0.75	-5.25	6.75	13.75	137.79	-0.94	0.77	7.79	2.03	3.75	9.42	16.74	147.54	-19.25	-12.00	-11.50	-10.75	17.19	10.87	4.09

981

870	1.83	1.80	-5.00	3.75	-0.75	-5.25	6.50	13.50	137.79	-0.13	1.02	7.66	2.03	3.88	9.42	16.61	147.54	-18.50	-10.25	-10.75	-10.25	17.19	10.20	4.01
875	1.79	1.90	-4.75	3.75	-0.75	-5.00	6.50	13.50	137.79	-0.94	1.09	7.66	1.91	3.88	9.29	16.61	147.43	-18.00	-9.75	-10.50	-9.75	17.19	17.77	4.03
880	1.74	1.75	-5.00	3.75	-0.75	-5.25	6.50	13.25	137.79	-1.25	0.59	7.48	1.91	3.50	9.23	16.36	147.54	-19.00	-11.50	-11.25	-10.50	17.06	14.29	4.06
885	1.70	1.65	-5.00	3.50	-0.75	-5.25	6.25	13.00	137.79	-0.75	0.90	7.48	1.78	3.56	9.11	16.42	147.54	-18.50	-10.75	-11.00	-10.25	17.06	8.18	4.09
890	1.66	1.70	-4.75	3.50	-0.75	-5.00	6.25	12.75	137.69	0.06	1.09	7.48	1.91	3.88	8.98	16.24	147.54	-19.25	-10.00	-10.25	-9.75	17.06	12.03	4.06
895	1.61	1.60	-4.75	3.25	-0.75	-5.25	6.00	12.75	137.79	-1.88	0.77	7.48	1.91	3.56	8.98	16.36	147.54	-19.75	-11.75	-11.50	-10.50	17.06	13.31	4.05
900	1.57	1.60	-4.75	3.25	-0.75	-5.25	6.00	12.75	137.69	-1.19	0.71	7.35	1.78	3.50	8.92	16.05	147.54	-18.75	-10.75	-11.00	-10.25	17.06	10.13	4.01
905	1.53	1.60	-4.75	3.25	-0.75	-5.00	6.00	12.50	137.79	-0.44	0.90	7.29	1.78	3.56	8.79	16.05	147.43	-19.25	-10.25	-10.50	-9.75	17.06	11.42	4.03
910	1.49	1.55	-4.75	3.25	-0.75	-5.25	6.00	12.50	137.79	0.31	1.09	7.16	1.78	3.88	8.79	15.92	147.54	-20.00	-11.50	-11.00	-10.00	17.00	15.57	4.06
915	1.45	1.55	-4.50	3.25	-0.75	-5.00	5.75	12.25	137.79	-1.88	0.46	7.10	1.72	3.38	8.79	15.74	147.43	-18.00	-10.00	-10.50	-9.75	17.00	13.61	4.01
920	1.41	1.35	-5.00	3.00	-0.75	-5.25	5.75	12.00	137.79	-0.94	0.71	7.10	1.72	3.38	8.73	15.86	147.54	-20.00	-11.75	-11.25	-10.25	17.00	7.45	4.00
925	1.37	1.30	-5.00	3.00	-0.75	-5.25	5.50	12.00	137.79	-0.13	0.90	7.10	1.78	3.56	8.61	15.74	147.54	-19.00	-10.75	-11.00	-10.00	17.00	10.13	4.09
930	1.33	1.30	-4.75	3.00	-0.75	-5.25	5.50	11.75	137.79	0.06	1.21	7.10	1.78	3.75	8.61	15.67	147.54	-20.25	-11.50	-11.00	-10.00	17.00	15.63	4.04
935	1.29	1.30	-5.00	3.00	-0.50	-5.25	5.50	11.75	137.79	-1.38	0.59	6.98	1.72	3.25	8.42	15.67	147.43	-19.25	-11.75	-11.50	-10.50	16.88	10.44	3.97
940	1.26	1.15	-5.00	2.75	-0.75	-5.25	5.25	11.50	137.79	-0.75	0.71	6.85	1.72	3.25	8.48	15.42	147.43	-17.00	-9.75	-10.50	-9.75	16.88	8.12	3.96
945	1.22	1.25	-4.75	2.75	-0.75	-5.00	5.25	11.50	137.79	0.06	1.02	6.85	1.72	3.56	8.42	15.42	147.54	-20.25	-11.00	-10.75	-9.75	16.88	15.20	3.95
950	1.18	1.05	-5.00	2.75	-0.75	-5.25	5.00	11.25	137.69	-1.50	0.90	6.79	1.59	3.50	8.42	15.36	147.43	-19.50	-10.00	-10.50	-9.75	16.88	4.27	4.02
955	1.15	1.20	-4.50	2.75	-0.75	-5.00	5.00	11.25	137.69	-1.19	0.59	6.66	1.72	3.19	8.23	15.17	147.43	-18.25	-8.75	-9.50	-9.00	16.88	18.07	3.97
960	1.11	1.05	-4.75	2.50	-0.75	-5.25	5.00	11.00	137.69	-0.50	0.77	6.66	1.72	3.25	8.29	15.24	147.43	-21.00	-12.00	-11.25	-10.25	16.88	8.36	3.95
965	1.08	1.10	-4.75	2.50	-0.75	-5.00	5.00	11.00	137.69	0.19	1.02	6.54	1.72	3.56	8.23	15.05	147.43	-18.75	-10.00	-10.25	-9.75	16.88	9.52	4.03
970	1.05	1.00	-4.75	2.50	-0.75	-5.00	4.75	10.75	137.69	-2.06	0.59	6.54	1.72	3.19	8.23	15.05	147.43	-19.00	-10.00	-10.50	-9.75	16.88	11.72	3.95
975	1.01	1.05	-4.75	2.25	-0.75	-5.00	4.75	10.75	137.79	-1.00	0.59	6.48	1.72	3.19	8.11	14.86	147.43	-19.75	-10.50	-10.50	-9.50	16.88	11.66	4.00
980	0.98	0.95	-4.75	2.25	-0.75	-5.00	4.75	10.50	137.69	-0.31	0.77	6.48	1.59	3.25	7.98	14.86	147.43	-17.50	-9.25	-9.75	-9.25	16.88	6.11	3.96
985	0.95	1.00	-4.50	2.25	-0.75	-4.75	4.50	10.50	137.69	0.31	1.02	6.48	1.72	3.50	7.98	14.86	147.43	-20.00	-8.75	-9.25	-8.75	16.88	13.31	3.98
990	0.91	0.90	-4.50	2.25	-0.75	-5.00	4.50	10.25	137.69	-2.06	0.40	6.35	1.59	3.06	7.92	14.67	147.43	-20.50	-10.75	-10.50	-9.25	16.88	13.19	3.97
995	0.88	0.80	-4.75	2.25	-0.75	-5.25	4.50	10.25	137.69	-1.00	0.59	6.35	1.59	3.06	7.92	14.67	147.43	-20.50	-11.00	-11.00	-9.75	16.88	5.98	3.90
1000	0.85	0.85	-4.75	2.00	-0.75	-5.00	4.50	10.25	137.69	-0.19	0.77	6.29	1.53	3.25	7.79	14.55	147.43	-17.25	-9.00	-9.50	-9.00	16.75	6.04	3.95
1005	0.82	0.80	-4.50	2.00	-0.75	-5.00	4.25	10.00	137.69	0.38	1.09	6.29	1.59	3.50	7.79	14.55	147.43	-20.50	-10.25	-10.25	-9.25	16.75	13.43	3.99
1010	0.79	0.70	-4.75	2.00	-0.75	-5.00	4.25	9.75	137.69	-1.69	0.40	6.16	1.53	2.94	7.67	14.49	147.43	-20.00	-10.00	-10.50	-9.50	16.75	5.37	3.98
1015	0.76	0.75	-4.25	2.00	-0.50	-4.50	4.25	9.75	137.69	-0.94	0.59	6.16	1.53	3.06	7.61	14.30	147.43	-16.75	-8.00	-9.00	-8.50	16.75	18.07	3.93
1020	0.73	0.70	-4.50	2.00	-0.75	-4.75	4.00	9.50	137.69	-0.13	0.77	6.16	1.59	3.25	7.61	14.17	147.43	-21.25	-12.00	-10.50	-9.25	16.75	10.62	3.94
1025	0.70	0.60	-4.75	1.75	-0.75	-5.00	4.00	9.50	137.69	0.38	1.09	6.16	1.53	3.38	7.61	14.30	147.43	-20.00	-10.25	-10.50	-9.50	16.75	7.14	3.95
1030	0.68	0.70	-4.50	1.75	-0.75	-4.75	4.00	9.50	137.69	-1.38	0.46	6.04	1.53	2.94	7.48	14.17	147.43	-18.50	-8.75	-9.50	-8.75	16.75	7.14	3.91
1035	0.65	0.60	-4.50	1.75	-0.75	-4.75	3.75	9.25	137.69	-0.81	0.59	5.98	1.53	3.06	7.48	14.05	147.43	-18.50	-7.75	-9.00	-8.25	16.75	7.14	3.86
1040	0.62	0.55	-4.50	1.75	-0.75	-4.75	3.75	9.00	137.69	0.00	0.90	5.98	1.53	3.25	7.61	13.99	147.54	-21.00	-11.00	-10.50	-9.00	16.75	8.85	3.91
1045	0.60	0.50	-4.50	1.75	-0.75	-5.00	3.75	9.00	137.69	-0.50	1.02	5.98	1.59	3.38	7.48	13.99	147.43	-19.25	-9.50	-10.00	-9.00	16.75	8.85	3.89
1050	0.57	0.55	-4.50	1.75	-0.75	-4.75	3.75	9.00	137.69	-1.25	0.46	5.85	1.53	2.94	7.48	13.86	147.43	-19.50	-9.00	-9.75	-9.00	16.75	6.84	3.96
1055	0.54	0.45	-4.50	1.50	-0.75	-4.75	3.75	8.75	137.69	-0.63	0.59	5.85	1.53	3.06	7.42	13.67	147.43	-20.25	-8.25	-9.25	-8.50	16.75	11.17	3.92
1060	0.52	0.45	-4.50	1.50	-0.75	-4.75	3.50	8.75	137.69	0.06	0.90	5.85	1.53	3.19	7.29	13.67	147.43	-20.50	-9.75	-10.00	-8.75	16.75	11.11	3.90
1065	0.49	0.40	-4.50	1.50	-0.75	-5.00	3.50	8.75	137.69	-1.00	0.77	5.79	1.53	3.19	7.29	13.67	147.43	-20.00	-10.00	-10.25	-9.25	16.75	9.40	3.92
1070	0.47	0.40	-4.50	1.50	-0.75	-4.75	3.50	8.50	137.69	-1.19	0.40	5.66	1.41	2.88	7.29	13.55	147.43	-19.00	-9.00	-9.50	-8.75	16.69	7.39	3.87
1075	0.44	0.40	-4.50	1.25	-0.75	-4.75	3.50	8.50	137.69	-0.50	0.71	5.66	1.53	3.06	7.17	13.49	147.43	-18.50	-7.75	-9.00	-8.25	16.69	7.02	3.89
1080	0.42	0.35	-4.50	1.25	-0.75	-4.75	3.25	8.25	137.69	0.19	0.90	5.66	1.53	3.19	7.11	13.30	147.43	-19.00	-9.00	-9.50	-8.50	16.69	7.20	3.85
1085	0.40	0.30	-4.25	1.25	-0.75	-4.75	3.25	8.00	137.58	-1.75	0.59	5.54	1.41	2.94	7.11	13.36	147.43	-19.00	-8.00	-8.75	-8.25	16.69	7.14	3.87

1090	0.37	0.35	-4.25	1.25	-0.75	-4.50	3.25	8.00	137.69	-1.00	0.46	5.54	1.41	2.88	7.11	13.30	147.43	-19.00	-7.50	-8.50	-7.75	16.69	7.14	3.89
1095	0.35	0.30	-4.25	1.00	-0.75	-4.50	3.00	8.00	137.69	-0.44	0.71	5.48	1.41	2.88	6.98	13.05	147.43	-19.00	-7.25	-8.50	-7.75	16.69	7.20	3.90
1100	0.33	0.30	-4.25	1.25	-0.75	-4.75	3.00	7.75	137.69	0.31	0.90	5.48	1.53	3.19	6.98	13.05	147.43	-21.50	-11.25	-10.00	-8.75	16.69	6.72	3.86
1105	0.31	0.20	-4.50	1.00	-0.75	-4.75	3.00	7.75	137.58	-2.19	0.46	5.48	1.41	2.88	6.98	12.99	147.43	-18.75	-8.75	-9.50	-8.50	16.69	6.78	3.82
1110	0.29	0.25	-4.25	1.00	-0.75	-4.50	3.00	7.75	137.69	-1.00	0.46	5.35	1.41	2.75	6.92	12.86	147.43	-18.75	-7.75	-8.75	-8.00	16.69	6.78	3.78
1115	0.27	0.20	-4.00	1.25	-0.75	-4.25	3.00	7.75	137.58	-0.31	0.71	5.29	1.41	2.88	6.79	12.80	147.43	-18.75	-7.25	-8.50	-7.75	16.69	9.71	3.83
1120	0.25	0.20	-4.00	1.00	-0.75	-4.50	2.75	7.50	137.69	0.31	0.90	5.29	1.41	3.06	6.79	12.80	147.32	-20.50	-8.25	-9.00	-7.75	16.69	10.93	3.82
1125	0.23	0.05	-4.25	0.75	-1.00	-4.50	2.75	7.25	137.69	-2.06	0.40	5.29	1.41	2.69	6.67	12.80	147.43	-19.50	-8.50	-9.25	-8.25	16.69	7.45	3.81
1130	0.21	0.05	-4.25	0.75	-1.00	-4.50	2.75	7.25	137.58	-1.00	0.46	5.16	1.28	2.75	6.67	12.55	147.43	-19.50	-7.75	-9.00	-8.00	16.56	7.45	3.80
1135	0.19	0.00	-4.25	0.75	-1.00	-4.50	2.75	7.00	137.58	-0.19	0.71	5.16	1.28	2.88	6.67	12.55	147.32	-19.50	-7.25	-8.50	-7.75	16.69	3.30	3.81
1140	0.17	0.15	-4.00	1.00	-0.75	-4.25	2.75	7.00	137.58	0.31	1.02	5.16	1.28	3.06	6.67	12.49	147.32	-19.00	-6.75	-8.25	-7.50	16.56	12.52	3.78
1145	0.15	0.05	-4.00	1.00	-0.75	-4.50	2.50	7.00	137.58	-0.94	0.59	5.04	1.28	2.94	6.67	12.30	147.43	-19.50	-7.75	-8.75	-7.75	16.56	14.41	3.79
1150	0.13	-0.05	-4.25	0.75	-1.00	-4.50	2.50	7.00	137.58	1.19	1.21	5.04	1.41	3.50	6.61	12.36	147.43	-18.75	-8.00	-8.75	-8.00	16.69	6.41	3.78
1155	0.11	0.05	-4.00	0.75	-0.75	-4.25	2.50	6.75	137.58	0.31	1.52	5.04	1.41	3.75	6.61	12.36	147.43	-20.25	-7.25	-8.25	-7.50	16.69	4.95	3.78
1160	0.10	0.10	-4.00	0.75	-1.00	-4.00	2.50	6.75	137.58	-1.56	0.40	4.98	1.28	2.75	6.42	12.05	147.32	-17.25	-6.25	-7.75	-7.00	16.56	9.77	3.72
1165	0.08	-0.05	-4.00	0.75	-0.75	-4.25	2.25	6.50	137.58	-0.81	0.59	4.98	1.28	2.88	6.48	12.17	147.32	-21.00	-7.75	-8.75	-7.50	16.56	9.04	3.78
1170	0.06	0.00	-4.00	0.75	-0.75	-4.00	2.25	6.50	137.58	0.19	0.77	4.98	1.41	3.06	6.48	12.05	147.43	-16.50	-6.75	-8.00	-7.00	16.56	5.98	3.74
1175	0.04	-0.05	-3.75	0.50	-0.75	-4.00	2.25	6.50	137.58	-0.44	0.90	4.85	1.41	3.38	6.42	12.05	147.43	-21.25	-7.25	-8.25	-7.25	16.56	9.95	3.72
1180	0.03	-0.15	-4.00	0.50	-1.00	-4.25	2.25	6.25	137.69	-0.63	0.77	4.85	1.28	3.25	6.29	11.99	147.43	-17.75	-7.25	-8.25	-7.25	16.56	6.23	3.73
1185	0.01	0.00	-3.75	0.50	-0.75	-4.00	2.25	6.25	137.58	0.38	1.09	4.85	1.41	3.56	6.42	11.80	147.43	-19.25	-6.50	-7.75	-7.00	16.56	6.29	3.73
1190	-0.00	-0.05	-3.75	0.50	-0.75	-4.00	2.25	6.25	137.58	-0.63	0.77	4.85	1.28	3.38	6.29	11.67	147.43	-19.25	-6.50	-7.50	-6.75	16.56	6.29	3.70
1195	-0.02	-0.10	-3.75	0.50	-0.75	-4.00	2.00	6.00	137.58	-0.63	0.71	4.73	1.28	3.25	6.29	11.80	147.43	-19.25	-6.25	-7.50	-6.50	16.56	6.23	3.66
1200	-0.03	-0.15	-3.75	0.50	-1.00	-4.00	2.00	6.00	137.58	-0.13	0.77	4.73	1.41	3.25	6.17	11.55	147.43	-19.25	-6.25	-7.50	-6.50	16.56	6.23	3.70
1205	-0.05	-0.10	-3.75	0.25	-1.00	-3.75	2.00	6.00	137.58	-0.44	0.90	4.73	1.41	3.25	6.11	11.49	147.43	-19.25	-6.00	-7.25	-6.50	16.56	6.17	3.70
1210	0.00	-0.10	-3.75	0.25	-1.00	-3.75	2.00	6.00	137.58	-1.25	0.46	4.73	1.28	2.75	6.17	11.36	147.32	-19.25	-6.00	-7.25	-6.50	16.56	6.23	3.67
1215	0.00	-0.15	-3.75	0.25	-1.00	-3.75	2.00	5.75	137.58	-0.63	0.71	4.66	1.41	2.88	6.11	11.36	147.32	-19.50	-6.00	-7.25	-6.50	16.56	6.23	3.66
1220	0.00	-0.10	-3.75	0.25	-0.75	-3.75	2.00	5.75	137.58	0.31	0.90	4.66	1.41	3.06	6.11	11.49	147.32	-18.75	-5.50	-6.50	-6.00	16.56	0.00	3.66
1225	0.00	-0.15	-3.50	0.25	-1.00	-3.50	1.75	5.50	137.58	-2.19	0.46	4.54	1.28	2.69	5.98	11.17	147.32	-19.50	-4.00	-6.00	-5.25	16.56	6.65	3.66
1230	0.00	0.00	-3.25	0.25	-1.00	-3.50	1.75	5.50	137.58	-0.94	0.46	4.66	1.28	2.69	6.11	11.17	147.43	-20.00	-4.75	-6.75	-5.75	16.56	6.65	3.63
1235	0.00	0.10	-3.00	0.25	-1.00	-2.75	1.75	5.50	137.47	-0.31	0.71	4.54	1.28	2.75	5.86	11.17	147.43	-23.75	-4.50	-4.00	-3.25	16.56	14.65	4.24
1240	0.00	-0.10	-3.25	0.25	-1.00	-3.25	1.75	5.25	137.58	0.38	1.02	4.54	1.41	2.94	5.86	11.17	147.32	-22.50	-8.25	-3.75	-4.25	16.56	3.11	4.20
1245	0.00	0.10	-2.75	0.25	-1.00	-2.75	1.75	5.25	137.47	-1.75	0.40	4.54	1.28	2.44	5.86	11.11	147.32	-24.50	-10.25	-4.75	-4.00	16.69	15.38	4.26
1250	0.00	0.10	-2.75	0.25	-1.00	-2.75	1.75	5.25	137.58	-0.81	0.59	4.41	1.28	2.56	5.86	10.86	147.43	-23.50	-6.50	-4.50	-3.75	16.75	17.64	4.30
1255	0.00	-0.15	-3.00	0.25	-1.00	-3.25	1.50	5.00	137.47	0.00	0.77	4.41	1.41	2.75	5.79	10.86	147.32	-23.25	-7.50	-6.00	-5.00	17.00	5.68	4.25
1260	0.00	0.05	-2.75	0.25	-1.00	-2.75	1.50	5.00	137.47	0.38	1.02	4.41	1.28	2.94	5.67	10.74	147.32	-22.00	-6.50	-5.50	-3.00	17.06	0.00	0.01

SAS

APPENDIX VI

Example SAS Programs used

to merge meat quality data sets

and carry out analyses of variance

SAS Program to Merge Data and Compare Chilling Treatment and Control Results

```
FILENAME BEEFQUA1 "BEEFQUA1.DAT";
FILENAME BEEFMFI "BEEFMFI.DAT";
FILENAME BEEFQUA2 "BEEFQUA2.DAT";
FILENAME BEEFSLW1 "BEEFSLW1.DAT";
FILENAME BEEFRUN "BEEFRUN.DAT";
FILENAME BEEFSHER "BEEFSHER.DAT";

DATA FILEA;
INFILE BEEFQUA1;
INPUT RUN WEEKDAY $ MONTH $ DAY YEAR TREAT $ SIDE $ COLOUR
    WT RETAINED PH1 PH2 PH3 TEMP L1 A1 B1 L2 A2 B2 L3 A3
    B3 TRAY STTRAY FSTEAK;
IF WEEKDAY EQ 'Thur' THEN WEEKDAY='RThur';
STEAK1 = STTRAY-TRAY;
STEAK2 = FSTEAK-TRAY;
SRATIO = 100.0*(STEAK2/STEAK1);
STKDRP = 100.0-SRATIO;
PROC SORT DATA = FILEA;
BY RUN SIDE;

DATA FILEB;
INFILE BEEFMFI;
INPUT D1 $ D2-D4 RUN SIDE $ FILTER WGT40 WGT24 ;
MFI40 = 100*(WGT40-FILTER)/5.0;
MFI24 = 100*(WGT24-FILTER)/5.0;
DROP D1-D4;
PROC SORT DATA=FILEB;
BY RUN SIDE;

DATA FILEC;
INFILE BEEFQUA2;
INPUT RUN SIDE $ FCTAVG FCTMAX FCMAVG FCMMAX FCB FATGRADE
    RIBEYEW RIBEYEL MUSCLE FAT CUTABIL REA MARBLING
    QUAL $ YIELDG $;
PROC SORT DATA=FILEC;
BY RUN SIDE;

DATA FILED;
**********************************************INFILE BEEFSLW MISSOVER;
INFILE BEEFSLW1 MISSOVER;
INPUT RUN DAY $ SIDE $ TREAT $ TCODE $ MAG1 SLENGTH MAG2 SWIDTH;
SLENGTH = .095*SLENGTH/(10*MAG1);
IF SWIDTH NE . THEN SWIDTH =  .095*SWIDTH/MAG2;
```

```
PROC SORT DATA=FILED;
BY RUN SIDE;
PROC MEANS NOPRINT DATA=FILED;
BY RUN SIDE;
VAR SLENGTH SWIDTH MAG1 MAG2;
OUTPUT OUT=FILED MEAN= ;

DATA FILEE;
INFILE BEEFRUN;
INPUT RUN LIVWGT TREAT $ SIDEC $ SIDET $ RUW RTW R24W R6DW LUW LTW
L24W L6DW RPRESPH RPSTESPH RPRT RPSTT LPRESPH LPSTESPH LPRT
LPSTT  LHIP;
DROP SIDEC -- LHIP;

TREATMNT=TREAT;

IF SIDEC = 'L' THEN DO;
*  LEFT SIDE IS CONTROL ;
SIDE  = 'L' ;
TCODE = 'C' ;
UNTRMDWT = LUW ;
TRMDWT   = LTW ;
W24H     = L24W ;
W6D      = L6DW ;
PRESPH   = LPRESPH ;
PSTESPH  = LPSTESPH ;
PRESTMP  = LPRT ;
PSTESTMP = LPSTT ;
HIP      = LHIP ;
OUTPUT FILEE ;
SIDE  = 'R' ;
TCODE = 'T' ;
UNTRMDWT = RUW ;
TRMDWT   = RTW ;
W24H     = R24W ;
W6D      = R6DW ;
PRESPH   = RPRESPH ;
PSTESPH  = RPSTESPH ;
PRESTMP  = RPRT ;
PSTESTMP = RPSTT ;
HIP = .;
OUTPUT FILEE ;
END ;

IF SIDEC = 'R' THEN DO ;
SIDE = 'R' ;
TCODE = 'C' ;
UNTRMDWT = RUW ;
TRMDWT   = RTW ;
```

```
W24H    = R24W ;
W6D     = R6DW ;
PRESPH  = RPRESPH ;
PSTESPH = RPSTESPH ;
PRESTMP = RPRT ;
PSTESTMP = RPSTT ;
HIP = LHIP ;
OUTPUT FILEE ;
SIDE = 'L' ;
TCODE = 'T' ;
UNTRMDWT = LUW ;
TRMDWT  = LTW ;
W24H    = L24W ;
W6D     = L6DW ;
PRESPH  = LPRESPH ;
PSTESPH = LPSTESPH ;
PRESTMP = LPRT ;
PSTESTMP = LPSTT ;
HIP = . ;
OUTPUT FILEE ;
END ;
PROC SORT DATA=FILEE;
BY RUN SIDE;

DATA FILEF ;
INFILE BEEFSHER;
INPUT RUN SIDE $ SAMP1 TREAT $ FMAX1 EYLD1 EBRK1 FYSL1
    RUN SIDE $ SAMP2 TREAT $ FMAX2 EYLD2 EBRK2 FYSL2
    RUN SIDE $ SAMP3 TREAT $ FMAX3 EYLD3 EBRK3 FYSL3;
AFMAX=MEAN(FMAX1,FMAX2,FMAX3);
AEYLD=MEAN(EYLD1,EYLD2,EYLD3);
AEBRK=MEAN(EBRK1,EBRK2,EBRK3);
AFYSL=MEAN(FYSL1,FYSL2,FYSL3);

PROC SORT DATA=FILEF;
BY RUN SIDE;

DATA ALLFILES;
MERGE FILEA FILEB FILEC FILED FILEE FILEF;
BY RUN SIDE ;
DATA ALLFILES;
SET ALLFILES;
APH = MEAN(PH1,PH2,PH3);
AL  = MEAN(L1,L2,L3);
AA  = MEAN(A1,A2,A3);
AB =  MEAN(B1,B2,B3);
HUEANG1=ATAN(B1/A1);
HUEANG2=ATAN(B2/A2);
HUEANG3=ATAN(B3/A3);
```

```
HUEANG=MEAN(HUEANG1,HUEANG2,HUEANG3);
AHUEANG=ATAN(AB/AA);
CHROMA1=SQRT(A1*A1+B1*B1);
CHROMA2=SQRT(A2*A2+B2*B2);
CHROMA3=SQRT(A3*A3+B3*B3);
CHROMA=MEAN(CHROMA1,CHROMA2,CHROMA3);
ACHROMA=SQRT(AA*AA+AB*AB);
SHRINK=100*(TRMDWT-W24H)/TRMDWT;
DRIP=100*(TRMDWT-W6D)/TRMDWT;
REP = 1 + INT ((RUN-1)/3);
TREAT2=TREAT;
IF TCODE EQ 'C' THEN TREAT='CON';
IF TREAT EQ 'RC1' THEN TREAT = '1';
IF TREAT EQ 'RC2' THEN TREAT = '2';
IF TREAT EQ 'RC3' THEN TREAT = '3';
DROP PH1-PH3 L1-L3 A1-A3 B1-B3 HUEANG1-HUEANG3 CHROMA1-CHROMA3;
DROP SAMP1 SAMP2 SAMP3 _TYPE_ _FREQ_ LOC FMAX EYLD EBRK FYSL;

* OMIT/DELETE SUSPECT VALUES;
IF RUN EQ 26 THEN DELETE;
IF RUN EQ 35 THEN DO; SHRINK=.; DRIP=.; END;
IF RUN EQ 3 THEN DO; AB=.; HUEANG=.; AHUEANG=.; END;
IF RUN EQ 9 AND TCODE EQ 'C' THEN DO; FYSL2=.; AFYSL=.; END;
IF RUN EQ 24 THEN DO; TRMDWT=.; W24H=.; W6D=.; END;
IF RUN EQ 22 AND TCODE EQ 'C' THEN DO; EYLD3=.; AEYLD=.; END;
IF RUN EQ 28 THEN DO; TRMDWT=.; W24H=.; W6D=.; END;
IF RUN EQ 28 AND TCODE EQ 'C' THEN DO; FMAX1=.; EYLD1=.; EBRK1=.;
      FMAX2=.; EYLD2=.; EBRK2=.; FYSL2=.; AFMAX=.; AEBRK=.; AEYLD=.;
      AFYSL=.; END;
IF RUN EQ 32 THEN TEMP=.;
IF RUN EQ 34 AND TCODE EQ 'T' THEN DRIP=.;
IF RUN EQ 14 AND TCODE EQ 'C' THEN MFI40=.;
IF RUN EQ 2 OR RUN EQ 3 THEN DO; STTRAY=.; FSTEAK=.; STEAK1=.; STEAK2=.;
END;

PROC SORT DATA=ALLFILES;
BY TREATMNT;

PROC TABULATE F=11.4 FORMCHAR = '          ';
CLASSES TREAT;
VAR SRATIO STKDRP COLOUR AL AA AB ACHROMA AHUEANG APH MFI40 MFI24
   FCTAVG FCTMAX FCMAVG FCMMAX FCB FATGRADE FAT CUTABIL REA
   MARBLING SLENGTH SWIDTH AFMAX AEYLD AEBRK AFYSL LIVWGT
   TRMDWT W24H W6D SHRINK DRIP PRESPH PSTESPH PRESTMP PSTESTMP;
TABLES SRATIO STKDRP COLOUR AL AA AB ACHROMA AHUEANG APH MFI40
MFI24 FCTAVG FCTMAX FCMAVG FCMMAX FCB FATGRADE FAT CUTABIL REA
   MARBLING SLENGTH SWIDTH AFMAX AEYLD AEBRK AFYSL LIVWGT
   TRMDWT W24H W6D SHRINK DRIP PRESPH PSTESPH PRESTMP PSTESTMP,
TREAT,
```

```
   n*f=5.0 MEAN MIN MAX RANGE /CONDENSE;

PROC GLM NOPRINT OUTSTAT=ANOVA;
TITLE ' COMPARE EACH TREATMENT TO CONTROL';
BY TREATMNT;
CLASSES REP TCODE;
MODEL TEMP--FATGRADE FAT--MARBLING SLENGTH SWIDTH UNTRMDWT--
PRESPH PRESTMP FMAX1--DRIP = REP TCODE;
LSMEANS REP / PDIFF STDERR OUT=OUTMEANR;
LSMEANS TCODE / PDIFF STDERR OUT=OUTMEANT;

DATA ANOVA;
SET ANOVA;
DROP TEMP--DRIP;
IF _TYPE_ EQ 'SS1' THEN DELETE;
MS=SS/DF;

PROC TABULATE DATA=ANOVA FORMAT=8.4 FORMCHAR='          ';
CLASSES TREATMNT _NAME_ _SOURCE_ _TYPE_ ;
VAR DF MS F PROB;
TABLES MEAN*_NAME_, _SOURCE_, TREATMNT*(DF*F=5.0 MS F*F=6.2 PROB)
     / RTS=20 CONDENSE;

PROC TABULATE DATA=OUTMEANT FORMAT=8.3 FORMCHAR='          ';
CLASSES TREATMNT TCODE _NAME_;
VAR LSMEAN STDERR;
TABLES _NAME_, MEAN*(LSMEAN STDERR), TREATMNT*TCODE / RTS=20
CONDENSE;

PROC TABULATE DATA=OUTMEANR FORMAT=7.3 FORMCHAR='          ';
CLASSES TREATMNT REP _NAME_;
VAR LSMEAN STDERR;
TABLES _NAME_, MEAN*TREATMNT*(LSMEAN STDERR), REP / RTS=25
CONDENSE;
```

SAS Program to Compare Results Amongst Chilling Treatments

```
FILENAME BEEFQUA1 'BEEFQUA1.DAT';
FILENAME BEEFMFI 'BEEFMFI.DAT';
FILENAME BEEFQUA2 'BEEFQUA2.DAT';
FILENAME BEEFSLW1 'BEEFSLW1.DAT';
FILENAME BEEFRUN 'BEEFRUN.DAT';
FILENAME BEEFSHER 'BEEFSHER.DAT';

DATA FILEA;
INFILE BEEFQUA1;
INPUT RUN WEEKDAY $ MONTH $ DAY YEAR TREAT $ SIDE $ COLOUR
    WT RETAINED PH1 PH2 PH3 TEMP L1 A1 B1 L2 A2 B2 L3 A3
    B3 TRAY STTRAY FSTEAK;
IF WEEKDAY EQ 'Thur' THEN WEEKDAY='RThur';
STEAK1 = STTRAY-TRAY;
STEAK2 = FSTEAK-TRAY;
SRATIO = STEAK2/STEAK1;
PROC SORT DATA = FILEA;
BY RUN SIDE;

DATA FILEB;
INFILE BEEFMFI;
INPUT D1 $ D2-D4 RUN SIDE $ FILTER WGT40 WGT24 ;
WH0 = WGT40-FILTER;
W24 = WGT24-FILTER;
DROP D1-D4;
PROC SORT DATA=FILEB;
BY RUN SIDE;

DATA FILEC;
INFILE BEEFQUA2;
INPUT RUN SIDE $ FCTAVG FCTMAX FCMAVG FCMMAX FCB FATGRADE
    RIBEYEW RIBEYEL MUSCLE FAT CUTABIL REA MARBLING
    QUAL $ YIELDG $;
PROC SORT DATA=FILEC;
BY RUN SIDE;

DATA FILED;
**********************************************INFILE BEEFSLW MISSOVER;
INFILE BEEFSLW1 MISSOVER;
INPUT RUN DAY $ SIDE $ TREAT $ TCODE $ MAG1 SLENGTH MAG2 SWIDTH;
SLENGTH = .095*SLENGTH/(10*MAG1);
IF SWIDTH NE . THEN SWIDTH =  .095*SWIDTH/MAG2;
PROC SORT DATA=FILED;
BY RUN SIDE;
```

```
PROC MEANS NOPRINT DATA=FILED;
BY RUN SIDE;
VAR SLENGTH SWIDTH MAG1 MAG2;
OUTPUT OUT=FILED MEAN= ;

DATA FILEE;
INFILE BEEFRUN;
INPUT RUN LIVWGT TREAT $ SIDEC $ SIDET $ RUW RTW R24W R6DW LUW LTW L24W
    L6DW RPRESPH RPSTESPH RPRT RPSTT LPRESPH LPSTESPH LPRT LPSTT  LHIP;
DROP SIDEC -- LHIP;

TREATMNT=TREAT;

IF SIDEC = 'L' THEN DO;
*  LEFT SIDE IS CONTROL ;
SIDE  = 'L' ;
TCODE = 'C' ;
UNTRMDWT = LUW ;
TRMDWT   = LTW ;
W24H     = L24W ;
W6D      = L6DW ;
PRESPH   = LPRESPH ;
PSTESPH  = LPSTESPH ;
PRESTMP  = LPRT ;
PSTESTMP = LPSTT ;
HIP      = LHIP ;
OUTPUT FILEE ;
SIDE  = 'R' ;
TCODE = 'T' ;
UNTRMDWT = RUW ;
TRMDWT   = RTW ;
W24H     = R24W ;
W6D      = R6DW ;
PRESPH   = RPRESPH ;
PSTESPH  = RPSTESPH ;
PRESTMP  = RPRT ;
PSTESTMP = RPSTT ;
HIP = .;
OUTPUT FILEE ;
END ;

IF SIDEC = 'R' THEN DO ;
SIDE = 'R' ;
TCODE = 'C' ;
UNTRMDWT = RUW ;
TRMDWT   = RTW ;
W24H     = R24W ;
W6D      = R6DW ;
PRESPH   = RPRESPH ;
PSTESPH  = RPSTESPH ;
```

```
PRESTMP  = RPRT ;
PSTESTMP = RPSTT ;
HIP = LHIP ;
OUTPUT FILEE ;
SIDE = 'L' ;
TCODE = 'T' ;
UNTRMDWT = LUW ;
TRMDWT   = LTW ;
W24H     = L24W ;
W6D      = L6DW ;
PRESPH   = LPRESPH ;
PSTESPH  = LPSTESPH ;
PRESTMP  = LPRT ;
PSTESTMP = LPSTT ;
HIP = . ;
OUTPUT FILEE ;
END ;
PROC SORT DATA=FILEE;
BY RUN SIDE;

DATA FILEF ;
INFILE BEEFSHER;
INPUT RUN SIDE $ SAMP1 TREAT $ FMAX1 EYLD1 EBRK1 FYSL1
    RUN SIDE $ SAMP2 TREAT $ FMAX2 EYLD2 EBRK2 FYSL2
    RUN SIDE $ SAMP3 TREAT $ FMAX3 EYLD3 EBRK3 FYSL3;
AFMAX=MEAN(FMAX1,FMAX2,FMAX3);
AEYLD=MEAN(EYLD1,EYLD2,EYLD3);
AEBRK=MEAN(EBRK1,EBRK2,EBRK3);
AFYSL=MEAN(FYSL1,FYSL2,FYSL3);

PROC SORT DATA=FILEF;
BY RUN SIDE;

DATA ALLFILES;
MERGE FILEA FILEB FILEC FILED FILEE FILEF;
BY RUN SIDE ;
DATA ALLFILES;
SET ALLFILES;
APH = MEAN(PH1,PH2,PH3);
AL  = MEAN(L1,L2,L3);
AA  = MEAN(A1,A2,A3);
AB =  MEAN(B1,B2,B3);
HUEANG1=ATAN(B1/A1);
HUEANG2=ATAN(B2/A2);
HUEANG3=ATAN(B3/A3);
HUEANG=MEAN(HUEANG1,HUEANG2,HUEANG3);
AHUEANG=ATAN(AB/AA);
CHROMA1=SQRT(A1*A1+B1*B1);
CHROMA2=SQRT(A2*A2+B2*B2);
CHROMA3=SQRT(A3*A3+B3*B3);
```

```
CHROMA=MEAN(CHROMA1,CHROMA2,CHROMA3);
ACHROMA=SQRT(AA*AA+AB*AB);
SHRINK=100*(TRMDWT-W24H)/TRMDWT;
DRIP=100*(TRMDWT-W6D)/TRMDWT;
REP = 1 + INT ((RUN-1)/3);
TREAT2=TREAT;
IF TCODE EQ 'C' THEN TREAT='CON';
IF TREAT EQ 'RC1' THEN TREAT = '1';
IF TREAT EQ 'RC2' THEN TREAT = '2';
IF TREAT EQ 'RC3' THEN TREAT = '3';
DROP PH1-PH3 L1-L3 A1-A3 B1-B3 HUEANG1-HUEANG3 CHROMA1-CHROMA3;
DROP SAMP1 SAMP2 SAMP3 _TYPE_ _FREQ_ LOC FMAX EYLD EBRK FYSL;

* OMIT/DELETE SUSPECT VALUES;
IF RUN EQ 26 THEN DELETE;
IF RUN EQ 35 THEN DO; SHRINK=.; DRIP=.; END;
IF RUN EQ 3 THEN DO; AB=.; HUEANG=.; AHUEANG=.; END;
IF RUN EQ 9 AND TCODE EQ 'C' THEN DO; FYSL2=.; AFYSL=.; END;
IF RUN EQ 24 THEN DO; TRMDWT=.; W24H=.; W6D=.; END;
IF RUN EQ 22 AND TCODE EQ 'C' THEN DO; EYLD3=.; AEYLD=.; END;
IF RUN EQ 28 THEN DO; TRMDWT=.; W24H=.; W6D=.; END;
IF RUN EQ 28 AND TCODE EQ 'C' THEN DO; FMAX1=.; EYLD1=.; EBRK1=.;
      FMAX2=.; EYLD2=.; EBRK2=.; FYSL2=.; AFMAX=.; AEBRK=.; AEYLD=.;
      AFYSL=.; END;
IF RUN EQ 32 THEN TEMP=.;
IF RUN EQ 34 AND TCODE EQ 'T' THEN DRIP=.;
IF RUN EQ 14 AND TCODE EQ 'C' THEN WH0=.;
IF RUN EQ 2 OR RUN EQ 3 THEN DO; STTRAY=.; FSTEAK=.; STEAK1=.; STEAK2=.; END;

/*
PROC PLOT DATA=ALLFILES;
PLOT (TEMP STTRAY FSTEAK STEAK1 STEAK2 WH0 TRMDWT FMAX1--AB SHRINK DRIP)
    *RUN=TREAT;
*/

IF TCODE EQ 'C' THEN DELETE;

PROC GLM;
TITLE ' COMPARE 3 TREATMENTS';
CLASSES REP TREAT;
MODEL TEMP--FATGRADE FAT--MARBLING SLENGTH SWIDTH LIVWGT UNTRMDWT--PSTESTMP
    FMAX1--DRIP = REP TREAT;
LSMEANS REP / STDERR PDIFF;
LSMEANS TREAT / PDIFF STDERR;
```